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DISSERTATION

**METHODOLOGY FOR THE SYSTEM INTEGRATION OF
ADAPTIVE RESILIENCE IN ARMOR**

by

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September 2016

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**METHODOLOGY FOR THE SYSTEM INTEGRATION OF ADAPTIVE
RESILIENCE IN ARMOR**

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ABSTRACT

This dissertation introduces a novel augmentation to systems engineering methodology based on the integration of adaptive capacity, which produces enhanced resilience in technological systems that operate in complex operating environments. The implementation of this methodology enhances system resistance to top-level function failure or accelerates the system's functional recovery in the event of a top-level function failure due to functional requirement shift, evolutions, or perturbations. Specifically, the dissertation defines and proposes a methodology to integrate adaptive resilience and demonstrates its implementation in a relevant armor system case study. The conceptual validity of the methodology is proven through a physical comparative test and evaluation of the system described in the case study. The research and resulting methodology supplements and enhances traditional systems engineering processes by offering systems designers the opportunity to integrate adaptive capacity into systems, enhancing their resilient resistance, or recovery to top-level function failure in complex operating environments.

The research expands traditional and contemporary systems engineering, design, and integration methodologies, which currently do not explicitly address system adaptation and resilience. The methodology accomplishes this objective by defining adaptive design considerations, identifying controllable adaptive performance factors, characterizing adaptive performance factors and configurations, mapping and integrating adaptive components, and verifying and validating the adaptive components and configurations that achieve system requirements and adaptive design considerations. The utility of this research and methodology is demonstrated through development of an adaptive resilient armor system called the mechanically adaptive armor linkage (MAAL), which was designed, developed, and validated using the methodology for the system integration of adaptive resilience (MSIAR).

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LIST OF ACRONYMS AND ABBREVIATIONS

ABCT	Armor Brigade Combat Team
AD	Areal density
ADC	Adaptive design considerations
AR	Adaptive resilience
ASPEC	Attribute specification
ATPD	Automotive tank purchase description
CDD	Capability definition document
COE	Complex operating environment
DOD	Department of Defense
DOE	Design of experiments
DTIC	Defense Technical Information Center
ERDC	Engineer Research and Development Center
ERS	Engineered Resilient Systems
FEBA	Forward edge of battle area
GCV	Ground Combat Vehicle
GWOT	Global War on Terror
HH	High hardness steel
HMMWV	High mobility multipurpose wheeled vehicle
IBCT	Infantry Brigade Combat Team
IED	Improvised explosive device
IFV	Infantry fighting vehicle
kph	Kilometers per hour
KPP	Key performance parameters
KSA	Key system attributes
L1R	Level 1 resilience
L2R	Level 2 resilience
L3R	Level 3 resilience
MAAL	Mechanically adaptive armor linkage
MBSE	Model Based Systems Engineering
MILSTD	Military standard

mph	Miles per hour
MSIAR	Methodology for the system integration of adaptive resilience
OV-1	Operational view 1
PKM	Pulemyot Kalashnikova
psf	Pounds per square feet
PSPEC	Performance specification
RAM	Reliability, availability, and maintainability
RHA	Rolled homogenous armor
RPK	Ruchnoy Pulemyot Kalashnikova
RRS	Rapidly reconfigurable systems
SECDEF	Secretary of Defense
T1R	Type 1 resilience
T2R	Type 2 resilience
TARDEC	Tank Automotive Research Development Engineering Center
TDP	Technical drawing package
TRL	Technology readiness level
UHMWPE	Ultra-high molecular weight polyethylene
U.S.	United States of America
WMD	Weapons of mass destruction

EXECUTIVE SUMMARY

Systems engineers design, develop, and field traditional systems to address a set problem or fixed set of requirements that the system's functionality solves or fulfills. These traditional systems tend to operate at one optimized design point for a given set of external operational conditions to achieve a given top-level function or task. This approach, while acceptable for most systems, presents a significant functional limitation for systems that must operate or function in complex environments. Complex environments can be defined as environments in which operational conditions are unpredictable, experience disruptive perturbation, and rapidly shift.

This dissertation proposes a new system attribute called *adaptive resilience*, which enables a system to adapt its functional traits, structure, process, and/or identity in order to maintain or regain functional effectiveness in satisfying its top-level functional requirements. This attribute is particularly beneficial in complex operating environments. In order to achieve an adaptive resilient system, system designers and engineers must identify, account for, and incorporate the necessary range or capacity for adaptation early in the design and development process. This dissertation demonstrates such an integration methodology, which achieves the desired attribute of adaptive resilience.

All technological systems operating in complex environments are disadvantaged when they encounter operational circumstances that may cause them to fail to achieve and maintain their top-level function. Traditional static system designs often fail in complex operating environments due to their inability to readily adapt to changing functional requirements. Contemporary fixed system designs (design for robustness) are better suited for operation in uncertain environments. However, they likely possess parasitic capacity created by their robust nature and are ultimately susceptible to failure complex environments because they also employ fixed functional states. Parasitic capacity is underutilized functional capability that detracts from adjacent functional capabilities within a system. Adaptive resilient system designs possess adaptive physical components that enable the system to resist or recover from functional failure in complex operating environments in an agile fashion, while simultaneously mitigating the effects of parasitic capacity.

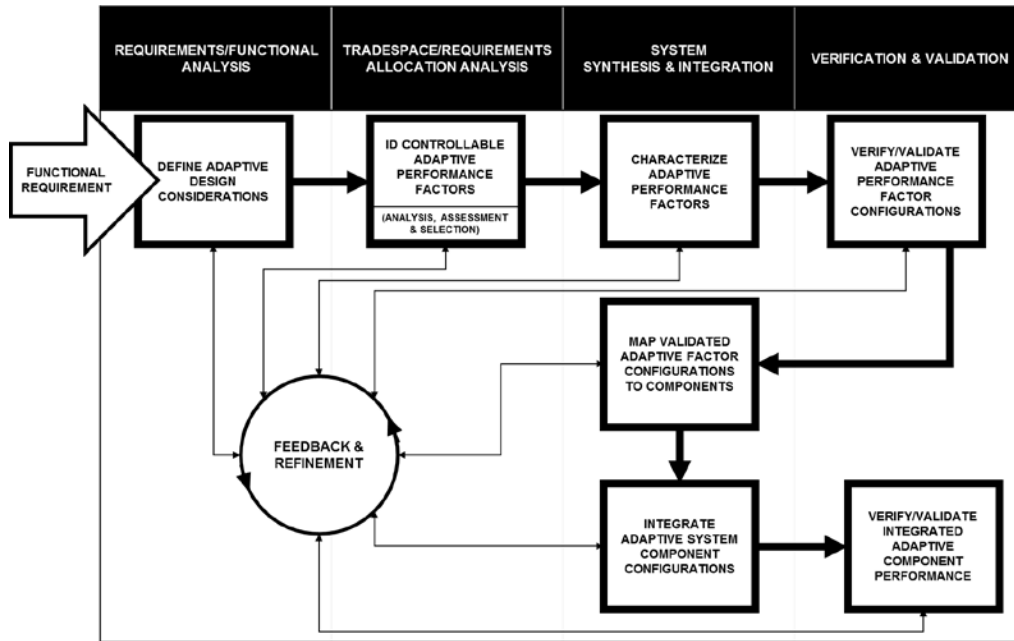
Within a system, adaptability is the key element that produces resilience. A system can only adapt to a purpose or a situation if it has the capacity to adapt or if some means of intelligence externally influences the system to adapt its use to new ends. Adaptive capacity is the critical system attribute that produces system resilience (Jackson 2009). Adaptive capacity can be defined as the extent to which a system can adapt or absorb a functional disturbance without completely losing operational performance of a top-level function (Jackson, 2009). Adaptive capacity can be further decomposed into modes of adaptability. Modes of adaptability are the ways and means to restructure or reconfigure a system's functional traits, structure, process, and/or identity. Two modes of adaptability—internal reconfiguration and external reconfiguration—serve to achieve the desired adaptation. Adaptations that occur through internal reconfiguration use means such as processes, mechanisms, and artifacts within the system to achieve desired functionality. Internal reconfiguration can occur through four means: operational variation, reallocation, degeneracy, and exaptation. External reconfiguration involves external means to achieve desired system functionality. Adaptive Mode 1 includes adaptive means present within the system at the time of the functional disturbance or incident. Adaptive Mode 2 involves external means (e.g., mechanisms, processes, and artifacts) not present in the system when its functionality was lost, but when applied after the fact, allows the system to regain its functionality. External reconfiguration occurs through three means: progressive scaling; redundant scaling; and replacement, repair, or healing.

In a systems engineering context, resilience is a system attribute that describes the system's ability to withstand or recover from perturbations and disruptions that exceed its functional tolerance. Resilience is a system state of being, without which a system would fail with the slightest external influence. Resilient ends are brought about by adaptive ways and means that exist in a system.

Adaptive resilience is a system attribute that enables a system to adapt its functional traits, structure, process, and/or identity in order to maintain or regain functional effectiveness in satisfying its top-level functional requirements. The conceptual need for adaptive resilience stems from the growing complexity present in modern system operating environments. As previously discussed, traditional technological systems are generally developed and fielded

with a set problem or static set of requirements that the system's functionality solves or fulfills. These systems generally operate at one optimized design point for a given set of external operational conditions to achieve a given set of principal/parent system tasks (Braha, Minai, and Bar-Yam 2006). This approach, although acceptable for most systems, presents significant functional limitations for systems required to operate or function in complex environments where those external operational conditions are unpredictable, experience perturbation, or rapidly shift. The purpose of adaptive resilience is to enable a system to adapt its functional traits, structure, process, and/or identity in operationally relevant timescales in order to maintain or remain functionally effective in satisfying its principle/top-level functional requirement in an unknowable and rapidly shifting environment. In order to achieve an adaptive resilient system, system designers and engineers must identify, account for, and incorporate the necessary range of performance–trait adaptability or adaptive capacity early in the design and development process. Therefore, an effective integration methodology is required to achieve system-level adaptive capacity during the system design and development process.

The methodology for the system integration of adaptive resilience (MSIAR) builds on prior design approaches and paradigms such as axiomatic, allocated design, set based design, as well as methods which employ Model-Based Systems Engineering (MBSE) and tradespace analysis to mitigate the consequences of uncertainty in the system's functional design. The MSIAR transcends beyond these methods by placing emphasis on the adaptive resilient physical component design. By doing this the components are enabled to accommodate a broad range of functional requirements while simultaneously mitigating the effects of parasitic capacity. Figure 1 shows the integration methodology that is the focus for this dissertation.



This figure depicts the proposed methodology that integrates adaptive resilience into technological systems. The methodology supplements the steps of the existing systems engineering process to incorporate the adaptive capacity necessary for a system to attain functional resilience. This dissertation provides the foundational concepts on which the methodology is based, demonstrates its application on a relevant technological system, and validates the methodology's efficacy in achieving the desired attribute of adaptive resilience.

Figure 1. The Methodology for the System Integration of Adaptive Resilience.

The methodology utilizes seven high-level steps that can be decomposed to any requisite level of fidelity for the integration effort of interest. The seven steps are as follows:

1. Define adaptive design considerations
2. Identify controllable/adaptive performance factors
3. Characterize adaptive performance factor configurations
4. Verify and validate adaptive performance factor configurations
5. Map validated configurations to adaptive system components/modules
6. Integrate adaptive components and configurations into system
7. Verify and validate integrated component configurations and performance

In this study, this seven-step methodology was applied to the design of a novel armor system as a case study to demonstrate its efficacy in integrating the adaptive capacity that produces system adaptive resilience. The case study used the draft capability definition document for the U.S. Army Ground Combat Vehicle (GCV) as the basis for the protection, mobility, and transportability requirements. These requirements were used as the inputs to the methodology, which generated adaptive design consideration. These MSIAR-generated design considerations specified a range of protection, considerations for the competing mobility, protection interests, and limitations on the vehicle width for transportability purposes. These considerations are listed in Table 1.

Table 1. Adaptive Armor Design Considerations

Adaptive Armor Design Considerations:	
ADC 1:	The adaptive armor design must be able to prevent the penetrations of .30 cal APM2 threats at the threshold and .50 cal APM2 threats at objective levels through adaptive mode one (internal reconfiguration) and adaptive mode two (external reconfiguration) at 50% reduction of weight from a Fixed RHA Armor System.
ADC 2:	The adaptive armor design must achieve the maximum amount of ballistic protection from the least amount of weight.
ADC 3:	The integrated adaptive resilient armor design while integrated on the host GCV platform may not exceed 204 inches of total GCV system width during strategic transport.

These considerations were then used to identify controllable performance factors that relate to and influence the realization of the design considerations. These factors were characterized as potential means and ways to achieve the adaptive design considerations. The characterized configurations were then verified and validated adaptive system configurations. The adaptive factor configurations for the novel armor system were armor mass, dimensionality, and dynamic state. These system configurations were then mapped to physical system components that could achieve the adaptive ranges of armor system configuration. Once mapped to suitable physical components, the components were

integrated into the holistic armor systems and again verified and validated for overall armor system suitability in achieving the original requirements and adaptive design considerations.

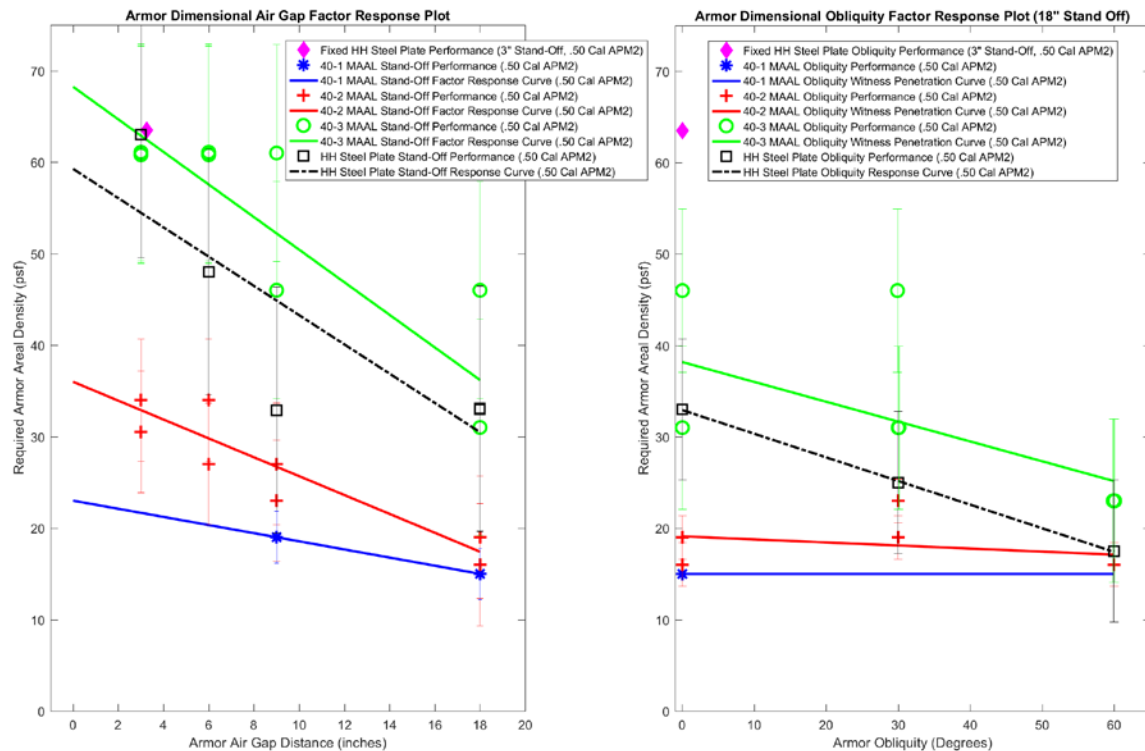
The case-study application of the methodology resulted in the creation of an adaptive resilient armor demonstrator, which employs a novel armor technology called mechanically adaptive armor linkage (MAAL). MAAL serves as a physical realization of the methodology's final product. This demonstrator physically achieved all requirements and adaptive design considerations, as well as all the adaptive factor configurations generated by the methodology. These configurations provided enhanced ballistic protection capability over a traditionally designed armor with similar material technology through adaptive internal and external design reconfigurations. Further, the adaptive resilient armor demonstrator showed how in certain circumstances, the methodology can eliminate the need to compromise on certain system components constrained by competing requirements. The outcomes of the design study are depicted in Table 2.

Table 2. MSIAR Results in Addressing the Adaptive Design Considerations

Adaptive Armor Design Constraints:		Results:
ADC 1:	The adaptive armor design must be able to prevent the penetrations of .30 cal APM2 threats at the threshold and .50 cal APM2 threats at objective levels through adaptive mode one (internal reconfiguration) and adaptive mode two (external reconfiguration) at 50% reduction of weight from a Fixed RHA Armor System. (T:24 psf; O: 40 psf)	Objective Threat Defeated at 16 psf.
ADC 2:	The adaptive armor design must achieve the maximum amount of ballistic protection from the least amount of weight.	See Above. Notional Objective Threat Defeated at 80% reduction in areal density from fixed armor system.
ADC 3:	The integrated adaptive resilient armor design while integrated on the host GCV platform may not exceed 204 inches of total GCV system width during strategic transport.	Prototype system buys back 36" of total vehicle width.

Ballistic evaluation of the adaptive component configurations demonstrated significant enhancement to the ballistic protection of the armor system. In some instances, ballistic protection against objective threats attained an 80% reduction in armor system weight over a nonadaptive resilient armor system. Nonadaptive armor systems can perform at this weight but with significant operational consequences for the width of the vehicle system

on which the armor was integrated. The adaptive resilient armor system can achieve this enhanced protection at a lighter weight while retaining the adaptive ability to collapse the enabling width, regaining the narrow width for mobility when needed. This is shown in the ballistic evaluation results shown in Figure 2.



These plots depict the core proof of concept ballistic experiments for the MAAL armor at key adaptive factor configurations. These plots show the performance at key dimensionality adaptive factor configurations. The bright pink diamond depicts the performance of a similar nonadaptive static armor. It does not have a range of performance because it does not have adaptive capacity needed to provide the range. The adaptive resilient armor can adapt its armor dimensionality and obliquity to provide objective threat protection at an armor areal density 50 psf less than the fixed nonadaptive armor. This weight can be used to regain vehicle performance with respect to mobility and transportability.

Figure 2. MAAL Ballistic Evaluation Plots.

The methodology for the system integration of adaptive resilience is shown to be a sound methodology for the creation of adaptive capacity within armor technological systems. The MSIAR enables these systems to adapt performance factors and realize a resilient state of operation for complex environments. This methodology was applied to the design of an adaptive resilient armor system. This system was based on relevant operational requirements

in which a top-level function was defined by a requirement often at odds with other critical requirements for the greater system of systems. The adaptive capacity realized in the adaptive resilient armor system provided the armor system the capability to meet and exceed top-level functional requirements in a fashion that did not implicate other requirements. The armor system provided a range of ballistic protection that handily met the requirements, and had extensible means available to rapidly address unknown/emerging penetrating threats.

This dissertation serves as an initial foray into integrating the attribute of adaptive resilience into a technological system. The proposed methodology incorporated concepts and principles from the maturing field of resilience engineering and merged them with systems design and engineering principles. This methodology was demonstrated on a single-case case study of the design of an adaptive resilient armor system, although it is meant for any technological system that operates in a complex operating environment and with competing requirements. Future research efforts for the methodology should center on applying the methodology to other systems that require adaptive resilience as a functional attribute. This future research should focus on refining the activities and processes associated with each step of the methodology.

This methodology makes possible many new applications for integrating adaptive resilience technological systems. These questions and many more will arise as systems engineers and designers employ and expand this approach. Adherence to the fundamental principles of systems engineering will serve as a guidepost in answering these complex questions. The methodology for the system integration of adaptive resilience has the potential to eliminate many of the system tradeoffs that have limited the functional utility of systems that operate in complex operating environments. The methodology also has the potential to enhance the operational effectiveness of systems that continually encounter operational challenges that stress or overmatch their ability to maintain top-level functionality. With proper discipline and application, this methodology enables users to enhance significantly the resilience of the systems they design.

PROLOGUE

THE NEED FOR ADAPTIVE RESILIENT SYSTEMS: A HYPOTHETICAL VIGNETTE

In April 2007, in Paktika Province, Afghanistan, members of the Third IBCT, “Spartans” of the 10th Mountain Division, entered their second year in Afghanistan, and as such, their second enemy offensive season. During the quiet winter months, the unit had been reconstituted with new up-armored High Mobility Multipurpose Wheeled Vehicles (HMMWV). The HMMWVs represented a technological response to the Taliban’s asymmetrical approach to offensive operations: conventional weapons coupled with improvised explosive devices (IEDs) employed in complex ambush scenarios. The new up-armored HMMWVs provided enhanced 360-degree protection from small-caliber individual and crew-served weapons, as well as from fragments and shrapnel from IEDs. The previous year was marked by significant casualties because of the lack of protection now provided by the new HMMWVs. The harsh winter brought tactical operations to a standstill, allowing the U.S. Army to invest in, upgrade, and enhance the protective capabilities of their operational forces and vehicle fleet. The ground commanders of the Spartan Brigade were optimistic about the 2007 offensive season. However, the Taliban had not been blind. They silently watched the truckloads of heavily armored HMMWVs pass through the few highways in this austere country. Realizing that their crew-served PKMs and RPKs would have little effect on these new vehicles, they adapted.

Early one crisp morning, a platoon of the Spartan Brigade conducted a mounted patrol. Confident in their new HMMWVs protective capability, the patrol traversed through the Manekandow Pass, a Taliban-watched pass that was expected to bring direct fire contact to the patrol. As the last vehicle rounded a narrow bend, automatic fire erupted throughout the valley. Spartan Soldiers fired their crew-served weapons to suppress and gain fire superiority over the asymmetric Taliban forces. The Spartan Soldiers emerged victorious, and the Taliban ambush was defeated. The patrol dismounted to clear the fighting positions from which they had been attacked. As the dismounted Soldiers climbed the ridgeline where they were ambushed, a Taliban sniper lay in wait on the opposite ridge. The sniper was not

targeting the dismounts, but the new up-armored HMMWV. He wanted to see if the newly fielded HMMWV could withstand the Taliban's newly purchased PTRS-41 anti-materiel sniper rifles. The sniper targeted the last vehicle in the convoy. The vehicle's remaining occupants, gunner, and driver, were providing over-watch of the dismounted patrol climbing the opposite ridge, unaware they were easy targets for this sniper. The sniper could not see the driver but wanted to shoot through the armor of the vehicle to both kill the driver and to send a chilling message to the Spartan Soldiers that their new vehicles were easily overmatched by the Taliban's new sniper rifles. The sniper estimated a bullet trajectory that would achieve both objectives.

The crack of the PTRS-41 sniper rifle destroyed the brief calm of the Manekandow Valley. The dismounted patrol returned overwhelming fire at all suspected enemy fighting positions on the opposite side of the valley from whence the shot rang out. However, their fire was ineffective. The sniper exfiltrated from his position before the patrol could return fire. A hidden photographer further up the valley recorded the incident and the actions of the Spartan Brigade patrol. The gunner in the targeted HMMWV screamed for a medic. The patrol medic approaching the vehicle noticed a smoking hole in the driver-side door armor of the vehicle. The crew cabin was filled with smoke and screams. The gunner dropped from his cupola, still screaming. As the medic opened the passenger side door, he saw the driver's door swing open. The HMMWV driver emerged, hacking and coughing, uninjured from the anti-materiel rifle's projectile. He ran over to the passenger side to assist the medic. The gunner's leg was sprayed with spall and shrapnel left when the projectile penetrated the vehicle—a minor but painful injury. The smoke erupting from the open doors was from a smoke grenade, which fortunately had stopped the bullet before it struck the driver. This was a close call, inches from a catastrophic result. The patrol leader looked at the gaping hole torn in the vehicle's armor from the sniper's bullet. His heart sank. Their new \$250,000 HMMWV with enhanced protection was easily penetrated by a \$2,000 heavy rifle and bullet that was fielded in 1941.

ACKNOWLEDGMENTS

This dissertation is dedicated to my wife, Amanda, my daughter, Alexandra, my son, Quinn, and all members of my family. In your “dealings” with me, you have evolved to a robust state of adaptive resilience. Thank you and I love you. Always.

A special thank you to James Mason, Emily Neville, Cynthia Crawford, Casey Brandt, and John Schmitz of the U.S. Army TARDEC Center for System Integration. Their assistance with the physical design, fabrication, and assembly of the Adaptive Resilient Armor Demonstrator was instrumental to the success of this research. A special thanks also goes out to Matthew Magner and the range team of the U.S. Army TARDEC SABL for their assistance in the experimental ballistic characterization of the adaptive resilient armor system. I would also like to thank Tongli Lim, Tanya McKnight, Patrick Stewart, and Kenneth Foos for the MAAL material failure analysis they conducted on MAAL samples.

The ideas and concepts derived in this dissertation are tirelessly inspired by the sacrifices of men like 1LT Benjamin Hall, CPL Aaron Griner, and SGT Jasper Obakrairur, and all servicemen who have sacrificed greatly to advance the ideals of our Republic. May we be resilient to the loss of such brave souls and adapt our methods so that their loss is not needlessly repeated.



Left to right: 1LT Benjamin Hall (source: Arlington Cemetery, <http://arlingtoncemetery.net/bjhall.htm>); CPL Aaron Griner (source: Veterans Parade, <http://veteransparade.blogspot.com/2008/08/cpl-aaron-m-griner.html>); SGT Jasper Obakrairur (source: Iraq War heroes, <http://www.iraqwarheroes.org/obakrairur.htm>).

Lastly, I would like to thank all my professors, mentors, and those who influenced my life toward advanced intellectual studies, especially those members of my dissertation committee. Thank you.

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I. INTRODUCTION

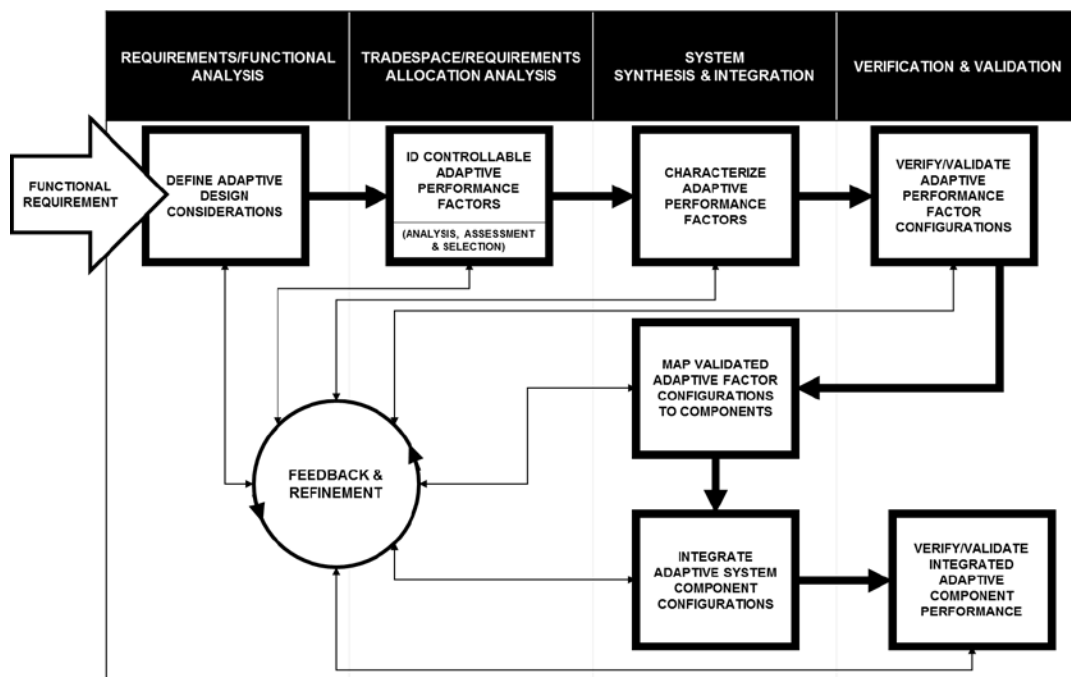
Systems engineers design, develop, and field traditional systems to handle a set problem or fixed set of requirements that the system's functionality solves or fulfills. These traditional systems tend to operate at one optimized design point for a given set of external operational conditions to achieve a given top-level function or task. This approach, while acceptable for most situations, presents significant functional limitation for systems that are required to operate or function in complex environments. Complex environments can be defined as environments in which the operational conditions are unpredictable, experience disruptive perturbation, or otherwise shift rapidly.

This dissertation proposes a new system attribute called *adaptive resilience*, which enables a system to adapt its functional traits, structure, process, and/or identity in order to maintain or regain functional effectiveness to satisfy its top-level functional requirements in complex operating environments. This attribute is particularly beneficial in complex operating environments. In order to achieve an adaptive resilient system, system designers and engineers must identify, account for, and incorporate the necessary range or capacity for adaptation early in the design and development process. This dissertation demonstrates an integration methodology that achieves the desired attribute of adaptive resilience. This seven-step methodology is depicted and briefly described in Figure 1. The methodology, which is discussed in detail in Chapter III, supplements the steps of the existing systems engineering process to incorporate the adaptive capacity necessary for a system to attain functional resilience. This dissertation provides the foundational concepts on which the methodology is based, demonstrate its application on a relevant technological system, and validate the methodologies efficacy in achieving the desired attribute of adaptive resilience.

A. BACKGROUND

All technological systems that operate in complex environments are disadvantaged when they encounter operational circumstances that may cause them to fail to achieve and maintain their top-level function. Technological systems that operate in combat environments demonstrate the validity of this idea. For example, a common military trailer has fixed

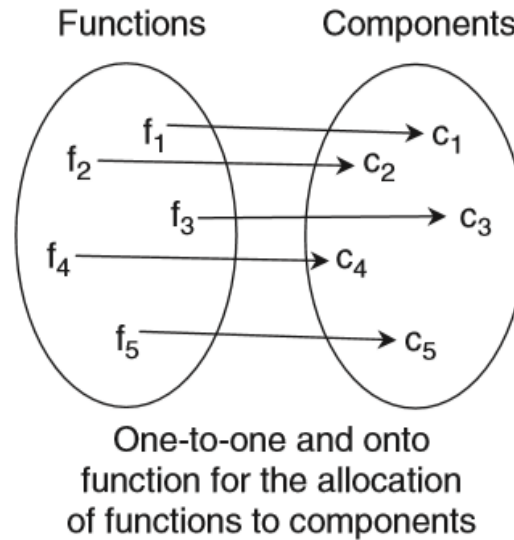
dimensions and a payload weight restriction that cannot be changed without a significant redesign. The system's functional constraints limit the utility of the trailer when it receives a nonstandard load that exceeds its traditionally designed capability. Another example might be a common military FM radio. Military FM radios operate in a set mode of frequencies. In today's modern era, many other pathways of digital and analogue communication exist, whether cellular network, satellite, or even the aging telephone lines. The common FM radio uses line-of-sight electromagnetic frequencies, which have limited range and are easily obstructed or jammed in complex operating environments. Soldiers are surrounded by other modes of voice communication but are constrained to a system that only exploits one of those available modes. In short, these legacy systems could provide far greater capability if they were designed and engineered using a different paradigm.



This figure depicts the proposed methodology that integrates adaptive resilience into technological systems. The methodology supplements the steps of the existing systems engineering process to incorporate the adaptive capacity necessary for a system to attain functional resilience. This dissertation will provide the foundational concepts on which the methodology is based, demonstrate its application on a relevant technological system, and validate the methodologies efficacy in achieving the desired attribute of adaptive resilience.

Figure 1. The Methodology for the System Integration of Adaptive Resilience.

Systems are commonly designed using an allocated architectural approach. One method for framing a system in an architectural fashion was proposed by Dennis Buede. Buede's (2009) approach defined functions that are traced to physical components through an allocated architecture. This approach is shown in Figure 2. Functions which reside in the functional architecture are mapped to an executing component in the physical architecture.

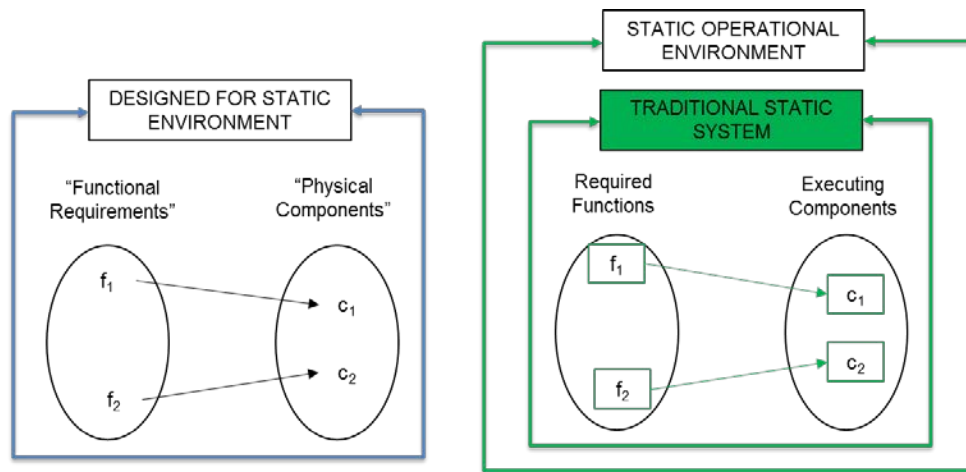


This figure depicts an allocated architecture in which system functions are traced to physical components that execute those functions. Buede emphasized that correct system design singularly maps one function to one component. Coupling of functions to components creates system design and operational challenges that are not preferred.

Source: Buede (2009, 290).

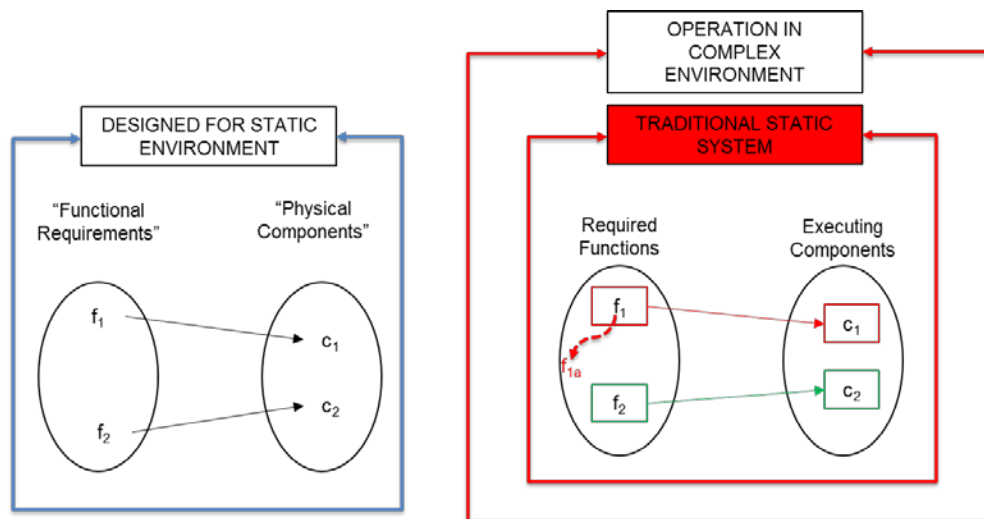
Figure 2. System Functions and Physical Components Mapped Through an Allocated Architecture.

This traditional approach to system design works very well for systems which operate in environments which are static or have minimal uncertainty. This is shown in Figure 3. However, what happens when functional requirements shift or evolve due to complexities in the system's operating environment? This situation is depicted in Figure 4. Often, the components that execute the functions fail to accommodate the functional requirement evolutions that occur in complex operating environments. In many of these circumstances, a significant redesign of the system or component must occur, which can be costly in both time and resources to address this shift in functional requirement.



Traditional, fixed system design works well in static operating environments with minimal uncertainty. In static operating environments, functional requirements seldom shift rapidly and evolve more predictably with the development of new technology. The optimized static physical components perfectly address the static functional requirements for the design.

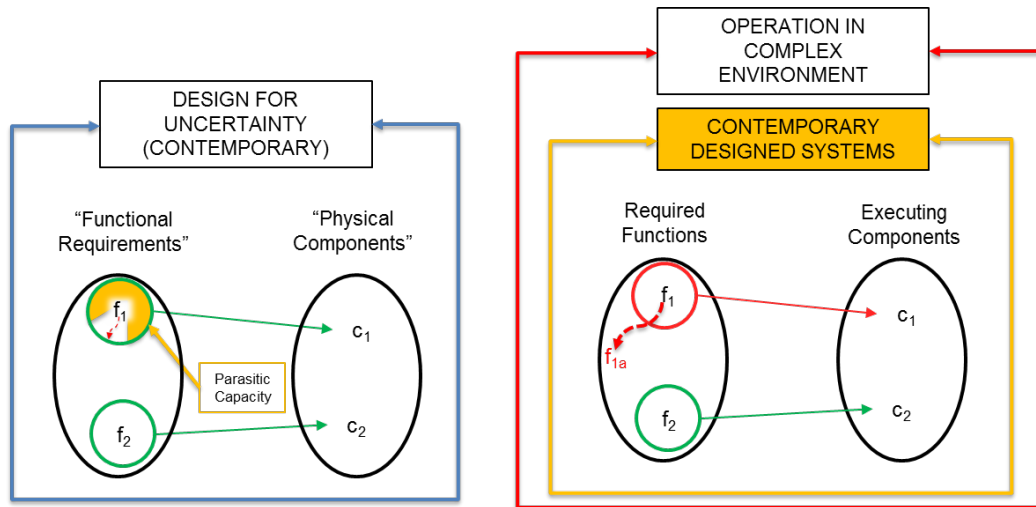
Figure 3. Traditional Systems in Static Operating Environments.



This figure depicts how a statically design system, when placed in to a complex operating environment will likely fail from rapid functional requirement evolution. The fixed, optimally designed components cannot accommodated functional requirement shifts (depicted with red dashed path) making them lose their ability to fulfill the system's designed functionality.

Figure 4. Traditional/Static System Design in Complex Operating Environments.

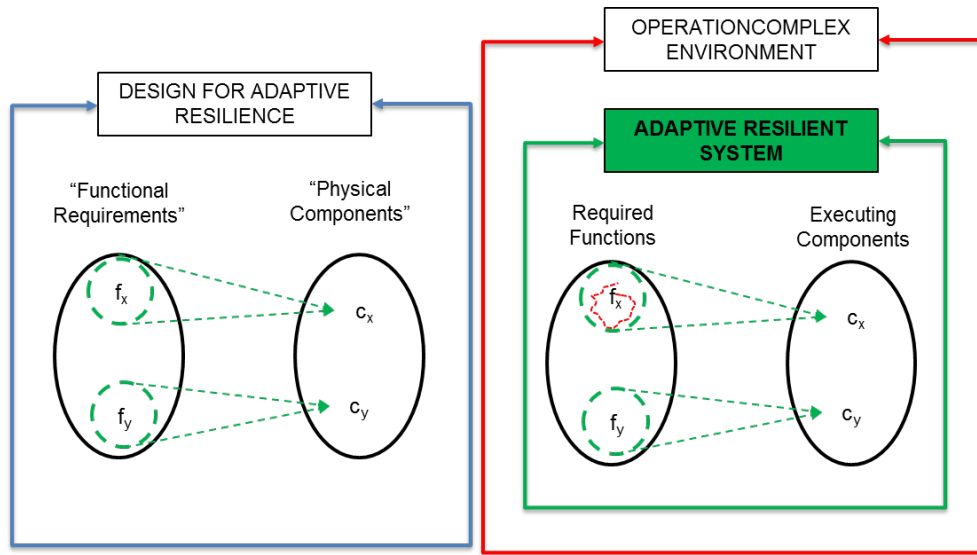
In an effort to address this issue, contemporary system design approaches, tools, and methods develop systems which have a robust accommodation to broader set of functional requirement states. These approaches include designs for robustness (Frey, Li 2004), set based design (McKenney, Kemink, Singer, 2011), and the many Model Based Systems Engineering (MBSE)-tradespace approaches (MacCalman, Beery, Paulo 2016). Generally, these approaches focus on developing functional requirements that are broadly applicable to a many operating conditions. In doing this the function can accommodate many states but in a fashion that is less than optimal. Set based design delays key technical functional design decisions until absolutely necessary, and makes the final decision more informed to address the functions actually required (McKenney. Kemink, and Singer, 2011). MBSE tradespace approaches also serve to inform the system designer of the most broadly suitable design points, enabling a greater amount of functionality across uncertain operating conditions (Beery, MacCalman, Paulo 2016). These approaches are effective but often have excessive parasitic capacity which affects other adjacent components or system's functional performance in the broader system or system of systems. Parasitic capacity, a new term generated from this dissertation research, refers to underutilized functional capability that detracts from adjacent functional capabilities within a system. A moniker that sums these approaches up well is that these types of systems are "jacks of many trades, but masters of none." Despite their robust design for broader functionality, they are still likely to be fixed systems which are susceptible to unpredictable functional requirement shifts and evolutions associated with the complex operating environment. Figure 5 shows this concept.



This figure depicts how contemporary designs have enhanced robustness (broad circular line around requirement) to the uncertainty of complex environments. However, in achieving this robustness the system traded away optimal performance in certain functions to achieve a level of performance for a broader set of functions. This situation oftentimes creates parasitic capacity (depicted in yellow) where the broader system capacity that is created or enabled by trades, seldom get employed. This makes the functions that are employed more often perform in a less than optimal state. Ultimately, robust system design are likely to employ static components and will encounter circumstances where their functional requirements will shift, rendering the components incapable of functional accomplishment.

Figure 5. Contemporary System Design in Complex Operating Environments.

Systems with adaptive resilience are designed with integrated component-level adaptive capacity. This adaptive capacity enhances the system by giving it means to accommodate and remain functional in the face of the requirement shifts or to rapidly recover functionality if the systems fall short in fulfilling their top-level functional requirement. Adaptive resilience also seeks to mitigate the added functional burdens associated with parasitic capacity which affect overall system performance. It does this by tailoring the physical component functionality to specific need at hand, vice the blanket approach of broadly traded or robust contemporary system designs. An architectural view of adaptive resilience is shown in Figure 6.



This figure depicts how an adaptive resilient system overcomes the challenges associated with operation in complex operating environments by creating a range of suitable functional performance (f_x) enabled by adaptive physical components (c_x vice c_1). The range of functional performance (dashed ring) provide functionality in an extensible fashion beyond the functional requirement, or just enough to satisfy the requirement while still allowing maximum efficiency within the design. Furthermore the system adapts to the design point that is most optimal for the functional need at hand. In doing this the effects of parasitic capacity are mitigated.

Figure 6. Adaptive Resilient Design in Complex Operating Environments.

In summary, traditional static system designs often fail in complex operating environments due to their inability to readily adapt to changing functional requirements. Contemporary fixed system designs are better suited for operation in uncertain environments, but are likely to possess parasitic capacity, and are ultimately susceptible to failure complex environments because their fixed functional nature. Adaptive resilient system designs possess adaptive physical components which enable the system to resist or recover from functional failure in complex operating environments in an agile fashion, while simultaneously mitigating the effects of parasitic capacity. A comparative summary depiction of these design approaches is shown in Figure 7.

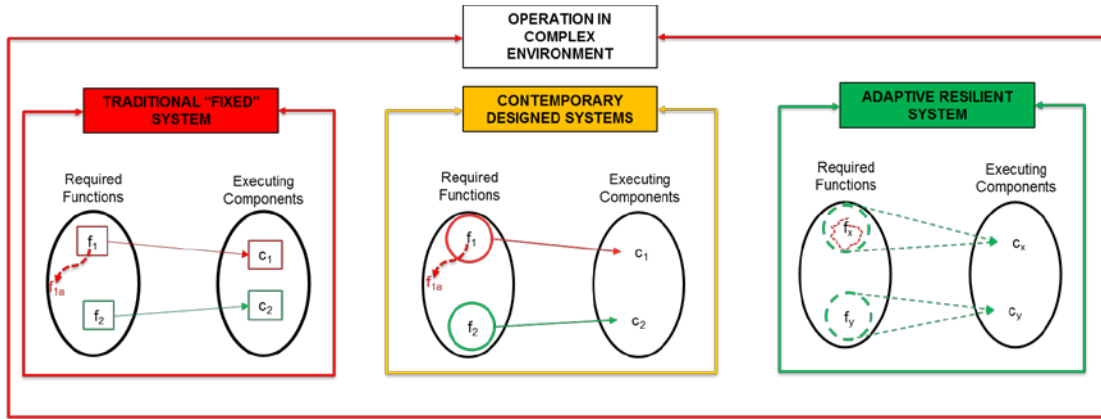


Figure 7. Comparison of Design Paradigms

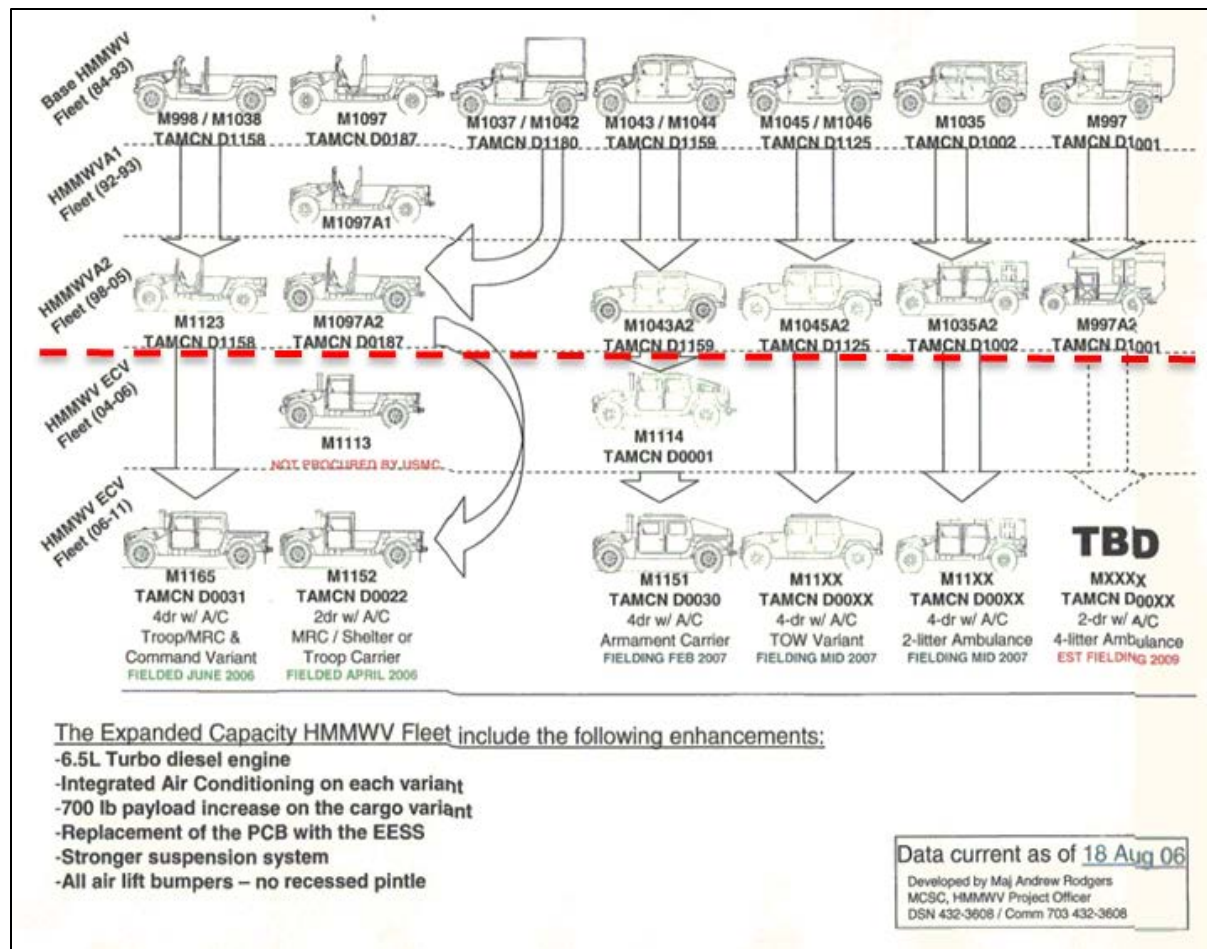
B. MOTIVATION

This functional resilience is the essence and value that the system attribute of adaptive resilience brings to systems which operate in complex operating environments. Combat is a highly complex environment in which the primary objective of the opposing forces is to overwhelm and diminish the combat power of the other. A driving factor or contributor to combat power is a belligerent's combat technology capability, thereby making combat technology an oppositional target for destruction or obsolescence. Combat technologies have traditionally been static in architecture and design, requiring cyclical upgrade, redesign, or abandonment. An example of this concept was the evolution of protective armor used on tactical vehicles during the global war on terrorism (GWOT).

In 2002, U.S. military forces invaded the country of Afghanistan to root out the Al Qaeda forces that planned the September 11, 2001, attack and the Taliban regime that hosted them. A year and a half later, U.S. forces invaded the country of Iraq under the auspices of preventing proliferation and growth of their dictator's weapons of mass destruction (WMD) arsenal. The U.S. and coalition forces, structured for a conventional fight, greatly overmatched both opposing forces encountered in these countries. Operations in both countries rapidly converted from conventional warfare to counterinsurgency, forcing the U.S. military to utilize its equipment in a nondoctrinal fashion. A particular example of this is how the military employed tactical vehicles. Tactical vehicles, unlike combat vehicles, are generally designed for operations behind the forward edge of the battle area (FEBA), such as

conducting logistics, reconnaissance, and security operations. During counterinsurgency operations, the conventional boundaries of the battle area disappeared. Although not high intensity, the battlefield enveloped the tactical vehicles, which were being engaged with weapon systems designed to destroy heavily armored combat vehicles (Kempinski and Murphy 2012).

After recognizing this new engagement style, the U.S. Department of Defense (DOD) engineers, scientists, and acquisition community rapidly evolved and developed vehicle survivability solutions to protect the Soldiers operating in this complex, asymmetrical-threat environment. The first evolution involved the “up-armoring” of the tactical vehicle fleet to protect against small arms fire and roadside bombs called improvised explosive devices (IEDs; Zoroya 2013). An example of this reaction is depicted in Figure 8.

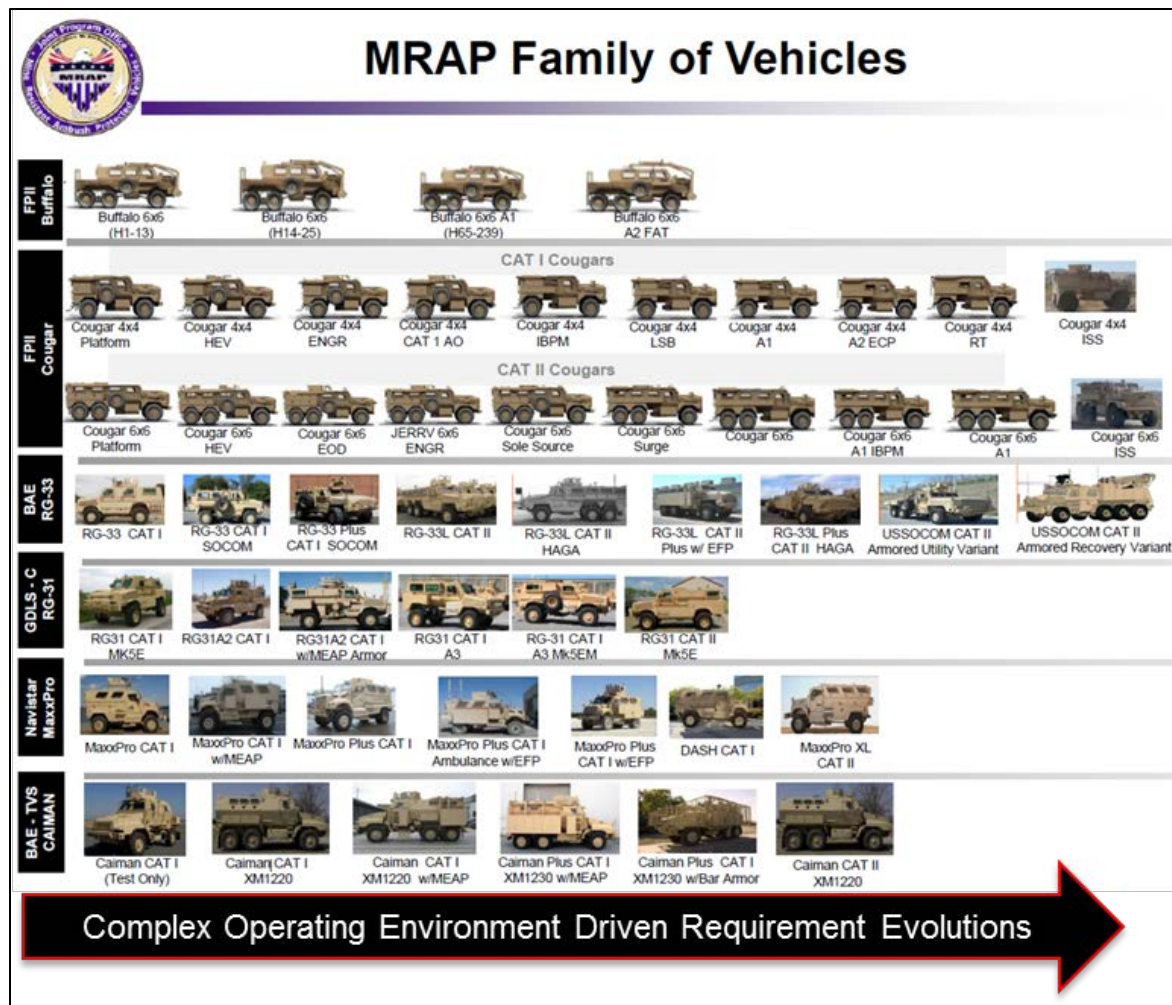


This figure shows that for much of its life cycle, the HMMWV remained static in its design. With the initiation of the GWOT, complex threat conditions drove rapid requirement changes in the HMMWV protection levels. These changes appear below the red dotted line. The changes created implications on other vehicle subsystems, causing costly second- and third-order effects to the vehicle requirements. These effects required engine upgrades and increased suspension capacity. Source: Rodgers (2006).

Figure 8. Evolution of the HMMWV: 1984–2011.

With the up-armoring of the U.S. fleet of tactical vehicles, insurgents in Iraq and Afghanistan were forced to change tactics. The easily penetrated soft-skin and lightly armored tactical vehicles now had fully integrated armor kits supplemented with aluminum appliqué that protected the crew and occupants from small arms and IED fragmentation threats. In an effort to maintain the casualty rate they had been inflicting, insurgents began emplacing IEDs in the middle of the road to strike the relatively unprotected underbody of the vehicles. The effects of these attacks were generally catastrophic to the tactical vehicles and their crews. By this point, U.S. forces were acquiring and fielding M1114s and the new, comparable M1151 HMMWVs, which provided moderate underbody protection to the crew and occupants. However, this armor was easily overwhelmed with an increased IED charge weight. The HMMWV platform, already at its maximum capacity for add-on weight could not sustain further add-on armor without serious consequences to the handling, suspension, and structure to the vehicle. A new vehicle with greater capacity was required.

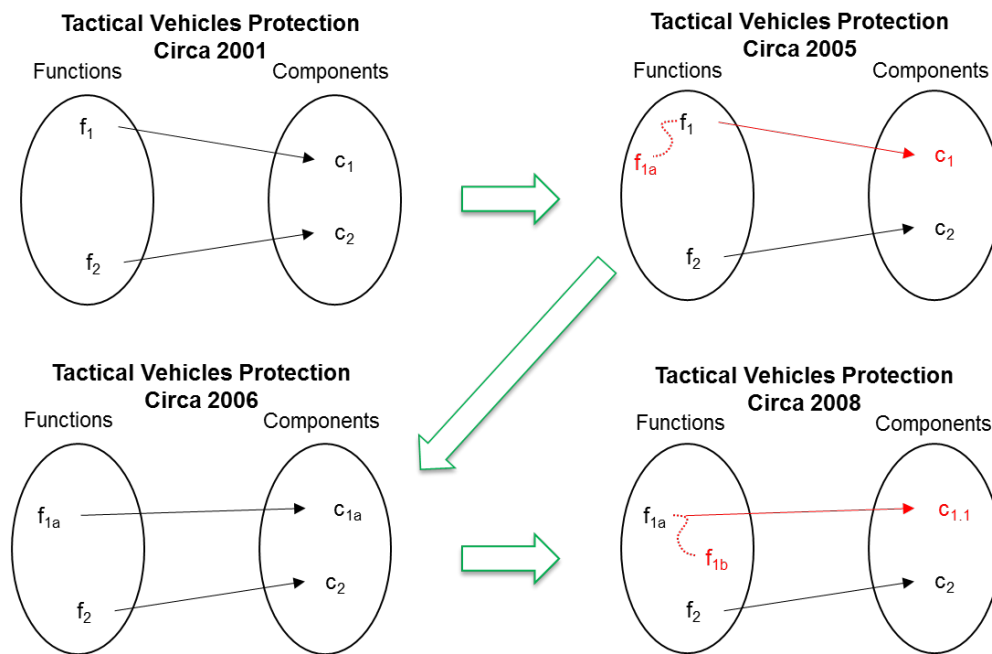
One of the other IED mitigation measures being employed in both theaters was the use of route-clearance patrols to detect, diffuse, and destroy the emplaced IEDs. These patrols had special vehicles elevated up to four feet off the ground, with monocoque hulls reinforced to sustain underbody mine blasts, fragmentation, and small arms fire. This was not a new concept: These vehicles had been in use for decades in Africa to clear mines. Seeing the integral protective capability, the U.S. Navy and Army, with influence from Congress, created the Joint Program Office Mine Resistant Ambush Protected (MRAP) vehicle program. Billions of dollars were spent, and thousands of these vehicles were procured and poured into Iraq and Afghanistan as an answer to the insurgents' simple change in IED emplacement tactics (Zoroya 2013). Figure 9. shows the family of MRAP vehicles that were used as an answer to the insurgent forces' evolving threat tactics.



This figure shows the MRAP family of vehicles, which evolved to address threats and other external requirement perturbations created by the complex operating environments of Iraq and Afghanistan during the GWOT. Source: Joint Program Office MRAP (2016).

Figure 9. Complex Operating Environment MRAP Evolutions.

With small arms fire, blast fragments, and now underbody blast threats effectively mitigated, insurgent forces in Iraq and Afghanistan had to begin employing threats of a more technical nature to overwhelm the new protective armor and hull designs employed on the MRAP vehicles. The insurgents' evolutionary response to this situation was to employ improvised anti-armor weapons with shaped charge liners to penetrate heavy armor deeply. This threat evolution shell game continued for many years. U.S. forces were continually in a reactionary state with respect to the enemy threat evolutions. This situation is depicted in an allocated architectural fashion in Figure 10.



Tactical vehicles were fielded with the intent for operation behind the forward line of troops where minimal protection levels were required (Static Operating Environment). During the GWOT, the forward line of troops was undefined and these tactical vehicles were thrust into overmatched threat environments (Complex Operating Environment) which were in a persistent state of evolution. Small arms ballistic threats, underbody IEDs, to anti-armor shape charge technology, all drove the required protection levels for combat vehicles higher and higher, creating numerous system redesigns over the course of the GWOT. The figure shows static functions which were allocated to static components that were suitable for the static operating environment behind the forward lines. In this role the vehicles were used for logistics, transportation and other benign purposes. When the forward line of troops was erased, that static environment transitioned to a complex environment. Now the static functions which were allocated to static components were no longer suitable for the complex threat environment they were thrust into.

Figure 10. Architectural View of Tactical Vehicle Evolutions
Driven by a Complex Operating Environment.

This reactionary approach was not a sound method to tackle the system challenges associated with operations in complex operating environments. A new system design paradigm was needed to mitigate these functional requirement perturbations, evolutions, and shifts.

C. PROBLEM STATEMENT

Traditionally engineered systems lack the ability to maintain agile top-level functionality when faced with rapid and significant requirement perturbations associated with operation in a complex environment (like those witnessed during the GWOT). The situation discussed in the example placed U.S. systems in a reactionary state of disadvantage rather than in a proactive or rapidly adaptive position of strength in the complex operating environment. This situation consumed significant engineering effort, time, and financial resources to address. Adaptive resilience enhances system functionality for these types of situations and can serve as a solution to address or mitigate this problem. However, the field of systems engineering does not have a coherent methodology to account for creating the adaptive capacity needed to enable adaptive resilience in technological systems.

A complex operating environment (COE) is defined as an environment that is not only unknown but also unknowable and constantly changing (Odierno, Perkins 2014). Developing systems with integral adaptive resilience can enhance their functional effectiveness in complex operating environments. The purpose of this dissertation is to develop and validate a methodology for the system integration of adaptive resilience (MSIAR). The concept of adaptive resilience was conceived as an observed solution from the field of resilience engineering to address the growing complexity present in modern system operating environments. As previously discussed, system engineers design, develop, and field traditional systems to handle a set problem or fixed set of requirements that the system's functionality solves or fulfills. These traditional systems tend to operate at one optimized design point for a given set of external operational conditions to achieve a given set of principle or top-level function(s) or tasks (Braha, Minai, and Bar-Yam 2006). This approach, while acceptable for most systems, presents significant functional limitations for systems that must operate or function in complex environments.

The purpose of adaptive resilience is to solve this problem and enable system's to maintain or remain functionally effective in satisfying their top-level functional requirements in unpredictable and rapidly shifting operating environments. In order to achieve an adaptive resilient system, systems designers and engineers must identify, account for, and incorporate the necessary range or capacity for adaptation early in the design and development process. Therefore, an effective integration methodology is required to achieve system-level adaptive resilience during that system's design and development process. This dissertation achieved this purpose through the accomplishment of the following objectives.

D. DISSERTATION RESEARCH QUESTIONS

The questions that guided this study included:

1. How can appropriate adaptive capacity be integrated into a technological system in order to achieve an enhanced state of functional resilience?
2. How do adaptive resilient system designers avoid or mitigate parasitic capacity while simultaneously realizing adaptations in operationally relevant timelines?
3. How can adaptive resilience be used to aid in better system development, such as enabling system to provide adaptive capability in uncertain, complex environments?

E. ASSUMPTIONS

The MSIAR is nested with the fundamental steps of systems engineering processes that exist in this field of study. Use of the MSIAR presumes that those who employ it have a competent comprehension of systems engineering and design, and the fundamental principles associated with each. This understanding will enable users of the methodology to apply each step of the methodology effectively and properly in the appropriate order for the challenge at hand.

In terms of this dissertation and its centerpiece methodology, it was assumed that a given system can achieve a state of adaptability. It was assumed that all systems and processes have factors that drive their output performance. In addition, it was assumed that those factors can be manipulated and controlled to achieve a desired output. The question or concern with adaptability was whether there is economy or value achieved in the proposed

adaptation. It was assumed that this methodology should only be employed when there is a clear and present value proposition to building a system's inherent adaptive resilience.

F. DISSERTATION CHAPTER SUMMARY

This dissertation is broken out into six total chapters, followed by an epilogue, and four appendices. Chapter II discusses the prior work and art which led to the development of the MSIAR. This chapter focuses on the definitions of adaptability and resilience and the state of the art in their application to system design and engineering. Chapter III seeks to thoroughly define and then describe step-by-step the MSIAR. Chapter IV describes a constructive application of the MSIAR in the design of an adaptive resilience armor system. This chapter opens with an armor technology primer to familiarize readers with the fundamental concepts of terminal ballistics. Chapter IV then walks step-by-step through the methodology and describes the activities of each step as there are applied to the adaptive resilient armor case study. Chapter V expands on Chapter IV and focuses on the verification, validation, and proof of concept for MSIAR. This chapter discusses the ballistic results and their implications on the enhanced functionality of the armor system. This chapter then portrays conceptual implementations of the adaptive resilient armor on a notional ground system platform. Chapter VI concludes the dissertation by summarizing the salient points and concepts, and then discussing where future research on this subject should focus. Appendix A provides the reader an example of a Technical Drawing package that resulted from the Chapter IV case study. Appendix B summarized the adaptive resilient armor ballistic evaluation results into a concise format for future reference. Appendix C is an additional study conducted by NPS on the failure modes that were observed during the adaptive resilient armor ballistic evaluations. This analysis will be critical for future research on proper material selection for the adaptive resilient armor that was developed. Appendix D concludes the dissertation with a glossary of terms used throughout this study.

II. PRIOR WORK

This dissertation contributes to the intellectual study of systems adaptability and resilience engineering. Researchers have studied resilience engineering and adaptability at length and found that these elements enhance system performance constructively in complex environments. Although a large body of knowledge, study, and analysis exists regarding resilience engineering and adaptability, a lack of research and design approaches hampers efforts toward effectively integrating these attributes into a technological system. This dissertation leverages the large body of knowledge, study, and analysis and fuses it with fundamental concepts of systems engineering to integrate these attributes into a technological system design.

A. ADAPTABILITY

Webster defined *adaptive* as showing or having a capacity for or tendency toward adaptation. Webster defined *adaptability* as the process of changing to fit some purpose or situation (Merriam Webster 2015). In other words, adaptability is the ability to exhibit adaptation. *Capacity* is the key word that stands out in the first definition. Systems can only adapt to a purpose or a situation if they have the capacity to adapt or are externally influenced by some means of intelligence designed to adapt that system's use to new ends. Most engineered technological systems are closed systems in the sense that they do not evolve or demonstrate emergent behaviors. That is, most engineered systems are deterministic: their functional output will never expand or grow outside of the operational states designed into the system from the start. Therefore, for an engineered system to achieve a state of adaptation, the capacity to do such must be designed or integrated into the system at conception. Although nondeterministic adaptation can be achieved in technical systems, it requires a level of intelligence or awareness, as well as a capacity to learn, that goes beyond the scope of this dissertation. This intelligence attribute is known as *equifinality*. Equifinal systems achieve similar outcomes in a given environment despite their disparate starting points (Bertalanffy 1950). Most deterministic systems are not equifinal. However, by introducing humans to the system, the potential for equifinality in a system increases.

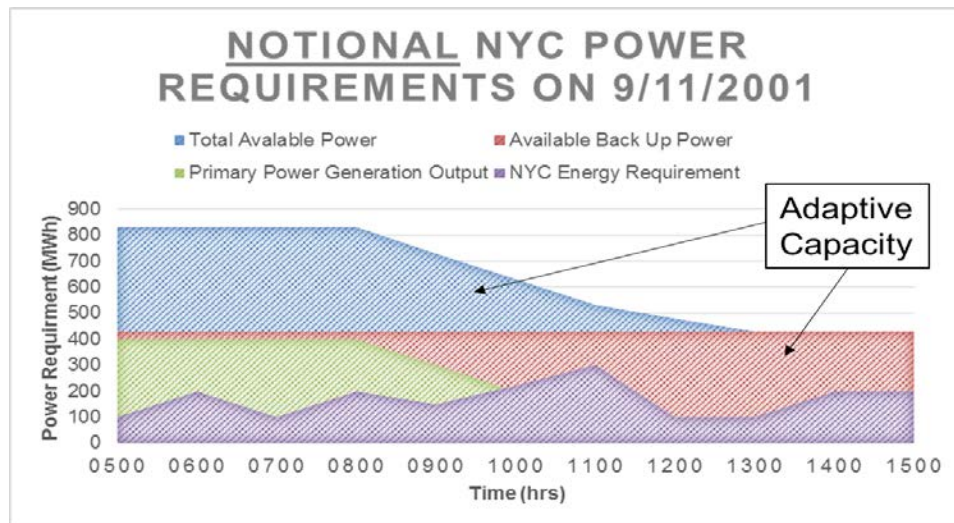
Humanity's ability to create intelligent, self-adaptable equifinal technological systems is in its genesis. Technical systems with the ability to adapt still require significant human interface to realize their adaptive potential. An example of this was the Apollo 13 mission during which the crew of this ship averted catastrophic system failure (Jackson 2009). Apollo 13 was to be the third intentional U.S.-manned lunar landing. The craft was launched on April 11, 1970, from the Kennedy Space Center, but the lunar landing was aborted when an oxygen tank exploded two days later, crippling the command and service modules that were critical to its mission. Despite this critical-system failure, the crew adapted systems and subcomponents of the ship, enabling it to sustain basic life support and allowing them to return safely to Earth on April 17. The Apollo 13 ship itself did not self-adapt and produce a feasible solution for crew and ship survival. Instead, it was the crew, the ship, and knowledge from Mission Control on Earth that allowed the mission to end without loss of life. The ship structure had been designed with a level of structural modularity. When Apollo 13 lost its main power, the crew moved to a smaller structural module in the ship and routed the remaining power sources to sustain them in this smaller hold (Jackson 2009). Thus, adaptability was the fundamental ingredient or attribute necessary for the system to be resilient (Jackson 2009). Had the Apollo 13 ship not possessed this level of adaptive capacity (e.g., crew, parts, subsystems), then the crew's resilient improvisational response would have failed, and the result of the mission would have been much different. In this instance, a question remains. When this ship was designed, was this adaptive capacity intentionally or unintentionally achieved?

1. Adaptive Capacity

Adaptive Capacity can be defined as the extent to which a system can adapt or absorb a functional disturbance without completely losing operational performance toward a top-level function (Jackson 2009). An example of adaptive capacity in operation was the New York City power loss and recovery on September 11, 2001. New York City had experienced power grid and infrastructure failures prior to the September 11 attacks, which had motivated energy providers to purchase backup generators to sustain the city's power needs in the event of a primary power-generation system failure. On September 11, 2001, the city sustained a significant disruption to its power infrastructure because of the loss of the World Trade

Center buildings; thus, the city completely lost electrical power. However, within five hours, power was restored to the city because of the adaptive capacity provided by the backup generators (Jackson 2009). This case demonstrates the value of this capacity provided. It also showed that the capacity was agnostic to the purpose for which it was created. The generators were purchased for rolling blackouts on the Eastern Seaboard, but were used to restore power during the terrorist attack. The point here is that the capacity may be unrelated to its original purpose as long as it delivers the function needed to fulfill that original purpose.

Adaptive capacity can be realized in two ways, both based on the functional requirements for the system. First, adaptive capacity can be produced through pure added performance, as shown in Figure 11.

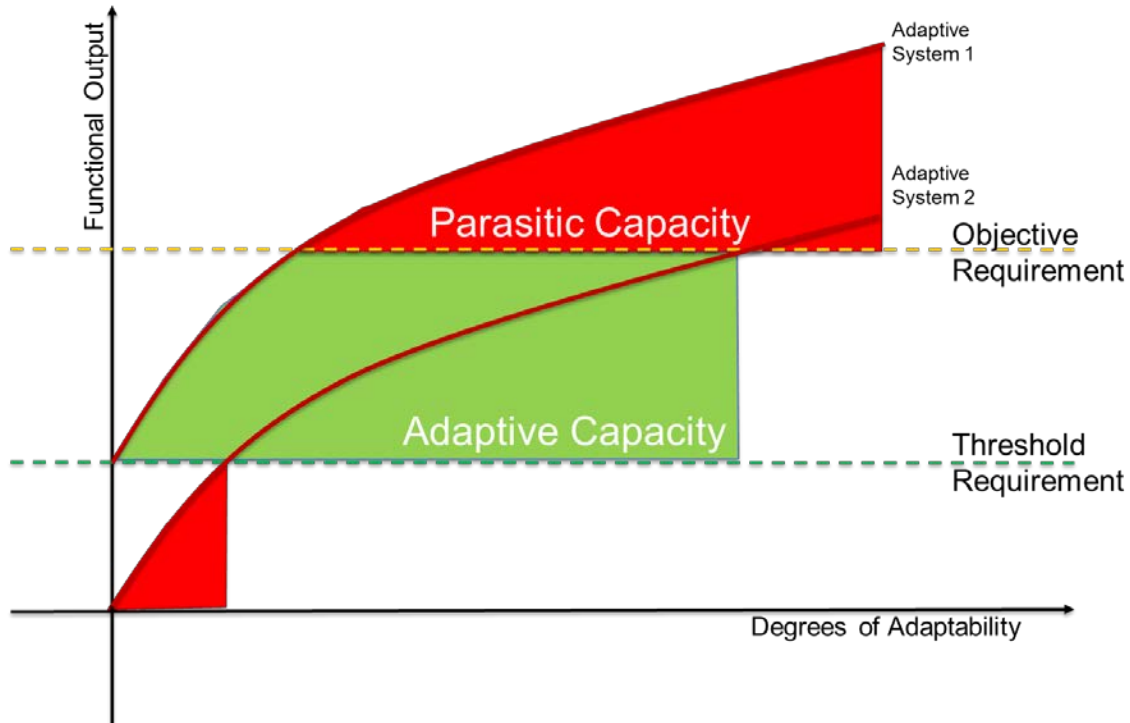


This figure is a notional depiction of the power requirements for New York City (purple), the power available from the primary power plant (green), the available power from the backup generator (red), and the total available energy available in blue. The excess power capacity is the adaptive capacity that the city had to work with when disruptions occurred. Backup generators provided this adaptive capacity.

Figure 11. Notional NYC Power Output on 9/11/2001.

Here, the baseline requirement was fulfilled with the primary power generators. The redundant backup generators doubled the available power for when needed. Second, the opposite of adaptive capacity would be an instance in which total available power would be just enough to meet the maximum total requirement, but that total maximum requirement would not always be used. In Figure 11. the primary power generators provided a capacity

that generally exceeded the need. For example, imagine this primary power output was the maximum requirement needed if every household in New York City was using all available power. This would likely never occur, but the primary power generators had the capacity to meet the demand if needed. The excess power not being used (difference in the green line and purple line) is excess capacity that could be exported to another city or used for another purpose. In addition, the output could be reduced when not needed and increased when needed. This capacity meets the requirement, but the need is not always equal to the requirement; therefore, the added capacity is left dormant or exported for alternate use. This alternate use could involve buying back system trades when there are competing interests. This concept is shown in Figure 12.



This figure depicts how adaptive capacity relates to parasitic capacity. Adaptive capacity is the key system attribute that brings about system resilience (Jackson 2009). Parasitic capacity extends beyond a functional requirement. Parasitic capacity can exist in robustly designed systems as a catch all approach to functional requirement accommodation, or it can exist in adaptive resilient system when extensible functional states are desired. In a perfect world, system designer would seek to minimize parasitic capacity.

Figure 12. Adaptive Capacity vs. Parasitic Capacity.

The ability to control or adapt the output readily is the key distinction that makes this adaptive capacity and not just unused parasitic capacity. For example, an M1 Abrams tank is designed to withstand heavy anti-armor threats. If placed in an operating environment in which only small arms are being used, this added protective capacity goes unused and actually become parasitic—the weight of this added protection inhibits mobility and requires the engine to consume additional fuel. By using extra fuel, the unused capacity projects consequences on other functional requirements. In contrast, an armor system with adaptive capacity could meet the requirement outright and possess added capacity readily available to protect against heavier threats. Alternatively, the adaptive capacity at its strongest could meet the requirement but also readily possess the capability to minimize the parasitic capacity that is not always needed. Thus, an adaptive resilient M1 Abrams would have the adaptive capacity to protect against the heavy threats when needed but be able to shed or exclude the unnecessary protection to give it the mobility or fuel efficiency previously inhibited. Another adaptive resilient M1 Abrams may at minimum meet the heavy threat protection requirements but have adaptive capacity readily available to scale that protection higher or in other ways along known protection factors to potentially account for unknown threats. This is the dichotomous nature of adaptive capacity; either approach makes systems better suited for the uncertainty associated with complex operating environments.

2. Modes of Adaptability

In order for a system to adapt, it must possess the ways and means to restructure or reconfigure functional traits, structure, process, and/or identity. Two modes of adaptability—internal reconfiguration and external reconfiguration—serve to achieve the desired adaptation.

a. Adaptive Mode 1: Internal Reconfiguration

Adaptations that occur through internal reconfiguration use means (e.g., processes, mechanisms, and artifacts) within the system to achieve desired functionality. Internal reconfiguration can occur through four means: operational variation, reallocation, degeneracy, and exaptation. The following examples of these adaptive modes use a robot as the adaptive system faced with challenges it must overcome in its operating environment.

(1) Operational Variation

Operational variation is the simplest of the modes. For example, imagine a robot was directed to open a door to move from one room to another. To open the door, it must reach out with its right hand and turn the knob in counter-clockwise fashion. However, if this robot were to encounter a doorknob that only turned in a clockwise direction, the robot would have to adapt the direction it twisted the knob to clockwise to transit between rooms. The operational variation mode involves employing the same means toward achieving a function but employing the means in a slightly modified way, in this case, changing the direction the robot turned the doorknob (clockwise to counterclockwise). This adaption is an example of operational variation; the means to conduct the function remained the same but were applied in a modified fashion.

(2) Reallocation

Reallocation is similar to operational variation in the sense that it uses the same means to perform the same function but takes the means from another location or area where it may not be currently needed. For example, imagine the same robot must open the door to move from one room to another; however, its right hand is broken, and it is therefore unable to twist the knob to accomplish this function. By adapting its approach to use its left hand to twist the knob, the robot would still be able to accomplish its task. This is an example of reallocation; the same type of means were employed but from an alternate location.

(3) Degeneracy

Degeneracy is a mode of adaption in which an artifact can serve as the means to conduct a prescribed function but is more appropriately qualified to accomplish other functions (Whiteacre and Bender 2010). For example, imagine the robot transiting between rooms is carrying a heavy object that has made its hands incapable of opening the door. Instead of setting the heavy object down, the robot adapts its approach by lifting its leg to manipulate the knob on the door with its foot, thereby opening the door to accomplish its function. Although the feet and legs are more appropriately suited for walking between rooms, these multifunctional artifacts can be effectively applied to functions like opening doors. This is a degenerate adaptation.

(4) Exaptation

Exaptation, also known as functional novelty, is a type of adaptation in which existing means are employed in novel ways when encountering new environments and challenges (Whiteacre and Bender 2010). For example, as the robot moves from room to room by opening doors, it may encounter a room with no doors to open but a ladder that leads to a higher level of the building where there are stairs to the room the robot must reach. By adapting the ways in which its hands, feet, and legs are used, the robot is able to transit between rooms in a novel fashion. Although very simple, this example shows the essence of exaptation in using existing means in novel ways.

b. Adaptive Mode 2: External Reconfiguration

External reconfiguration involves using external means to achieve desired system functionality. Adaptive Mode 1 includes adaptive means that are present within the system at the time of the functional disturbance or incident. Adaptive Mode 2 involves external means (e.g., mechanisms, processes, and artifacts) that were not present in the system when functionality was lost; however, when applied after the fact, the system regains its functionality. External reconfiguration occurs through three means: progressive scaling; redundant scaling; and replacement, repair, or healing.

(1) Redundant Scaling

Redundant scaling is a form of external adaptation in which the means to overcome a disturbance are appropriate but insufficient or lacking the amount of resources needed to overcome the disturbance. Using the robot and door example, redundant scaling could apply when a door is jammed and a single robot is too weak to open the door. The robot may have all the right means, but lack the magnitude or quantity of resources to overcome the force jamming the door. Redundant scaling could solve this problem by bringing in another robot to put its strength and means against the door to overcome the jam. All the required means are present: hands, legs, arms. However, one robot's strength was insufficient. An additional robot duplicated the means, thus adding the necessary strength to achieve functional success.

(2) Progressive Scaling

Progressive scaling is similar to redundant scaling in the sense that the original system lacks the magnitude of means to accomplish a task. However, progressive scaling differs somewhat: Instead of duplicating the means to accomplish the function, a single means of greater magnitude is applied. In the case of the jammed door, an adaptation that applies progressive scaling would replace the initial “normal-sized” robot attempting to open the stuck door with an NFL linebacker robot. The potency of the linebacker far exceeds that of the normal robot in opening the jammed door. Progressive scaling might also include providing the original robot with an enhancement to achieve the function. A crowbar, an explosive charge—or perhaps the door is only locked, and a key in the hand of the robot is all that is needed to open the shut door.

(3) Replacement, Repair, and Healing

In some situations, the disturbance disrupting the functionality damages the system, preventing functionality or making it susceptible to future functional failure. In these cases, a system that possesses an adaptive trait to heal, repair, or replenish itself would be of great value. Imagine if the robot were replaced by a man, who in trying to open the door, pushed so hard that he broke his arm. It would likely be impossible for the man to continue trying to open the door with a broken arm. However, the human body has evolved to possess a trait in which the structural/skeletal bones that support the body mend themselves when fractured. This process requires significant time to recuperate, with limited functionality of the damaged bone, but if set correctly, usually returns the appendage or region of the body to normal function and operation. Replacement, reparation, and healing can also occur under Adaptive Mode 1 (internal reconfiguration) if the means to do such was internal to the system when the disruption occurred.

3. Degrees of Adaptability

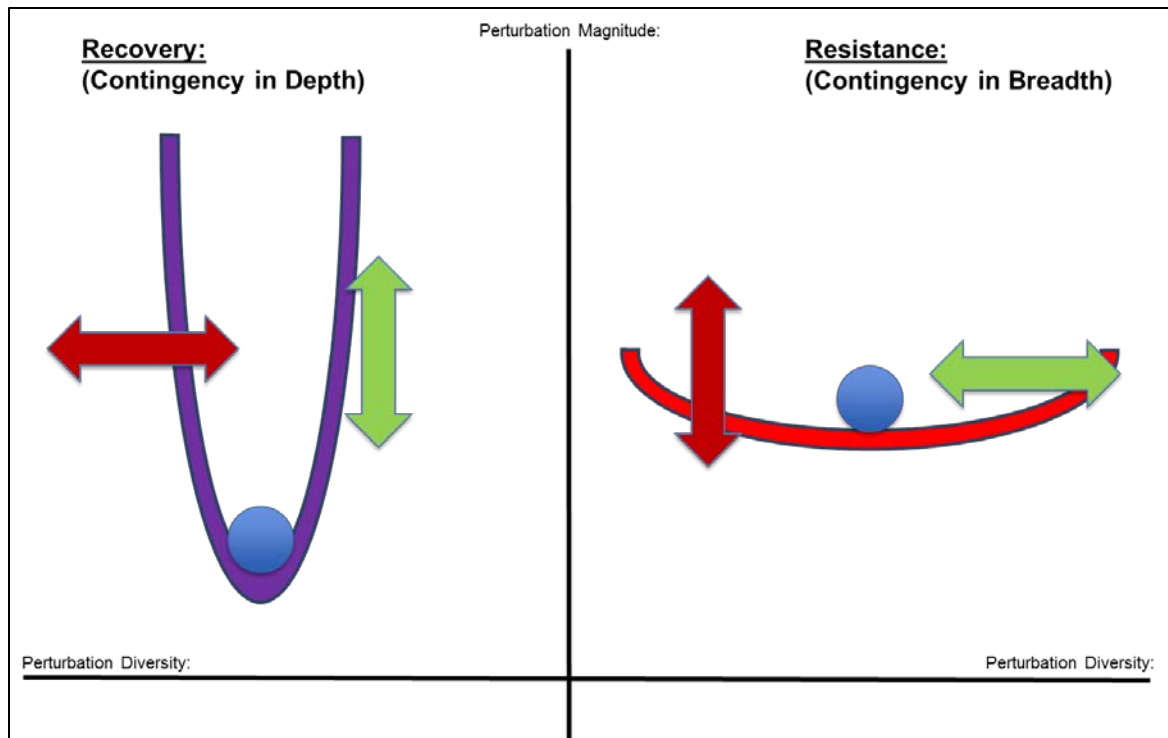
Degrees of adaptability is a measure of the number of adaptations a system has at its disposal. The degrees span the modes and submodes of adaptability. If a system has four internal reconfigurations and five external reconfigurations, then the overall system has nine degrees of adaptability. If a system has only four internal reconfigurations, each of which

uniquely uses the submode of reallocation, then the system has four degrees of adaptability. A greater number of degrees of adaptability is a key contributor to the concept of adaptive resilience. This will be discussed in subsequent paragraphs.

B. RESILIENCE

Webster defined resilience as the ability to regain strength, health, or success after something bad happens (Merriam Webster Dictionary 2015). In a systems engineering context, resilience is a system attribute that describes the system's ability to withstand or recover from perturbations and disruptions that exceed its functional tolerance. Resilience is a system state of being without which a system would fail with the slightest external influence. Note that two conditions are needed for a system to be defined as resilient: the ability to withstand disruptions and the ability to recover from disruptions. The founder of resilience theory, C. S. Holling, called these two conditions of resilience *ecological resilience* and *engineered resilience*, because these terms fit better with the context of ecology, his field of study (Holling, Allen, and Gunderson 2009).

An outstanding contextual analogy assists in visualizing Holling's idea of resilience: a ball and a bowl (Ruhl 2011). The ball and the bowl together represent a system's operational state. When the ball is contained within the bowl, the system is operating at a suitable state to achieve its top-level functionality. The shape of the bowl represents Holling's conditions of resilience. Tall, narrow bowls shaped like a vase or cup bearing steep sides are consistent with a system that possesses engineered resilience. Figure 13 depicts this concept.



This figure depicts the respective strengths and weaknesses of the two types of resilience: recovery and resistance. Recovery resilience possesses strengths in high perturbation magnitude situations. Resistance resilience has strength against a diverse range of perturbations. Adapted from Ruhl's description of resilience bowls (2011).

Figure 13. Ball-Bowl Basins.

A ball-bowl system with ecological resilience possesses shallow but widely separated walls, like a saucer with a wide area or surface to hold the ball. When either of the ball-bowl systems is in a state of operational equilibrium, the balls contained within are at rest in their bowl centers. If the bowl is lightly shaken, the ball rolls around, but does not roll out. The ball in the tall, narrow bowl remains near the bottom center, never straying far from this location. Even if it does roll up the sides of the bowl, it will quickly roll back down and recover its equilibrium operational position. The ball in the shallow, widely separated walls would likely roll all around the bowl basin but would resist rolling over the edge and out of the bowl. The ball in this bowl may take an arbitrary path back to the center of the bowl and therefore take longer to reach equilibrium. Now consider how different disturbances to the bowl shapes would produce different recovery or resistance responses. The tall-sided bowl may easily tip over and spill the ball out, but not the shallow, wide bowl. A strong latitudinal disturbance to the bowl may bounce the ball out of the shallow saucer but not out of the tall

vase. Conversely, a strong longitudinal disturbance to the bowls may bounce the ball out of the tall, narrow bowl; however, the broad area of the flatter basin bowl has a greater area to catch the bouncing ball and return it to its center. The bottom of the bowl represents the “attractor” to the equilibrium state, whereas the form of the basin defines the “disturbance capacity” within which the system state can move before crossing the failure threshold.

The wider the basin, the greater the number of system states that can be experienced without crossing the failure threshold. This shape gives the system wide latitude to accommodate diverse system states and disturbances but limited ability to accommodate disturbances of large magnitude within those diverse states. Tall, narrow bowls give a system limited latitude to accommodate diverse system states and disturbances but can typically handle disturbances of significant local magnitude. Engineered resilience strategies rely on strong attractors and limited system-state latitude, whereas ecological resilience strategies possess weaker attractors but tolerate a broader more diverse range of system states (Ruhl 2011). Systems can exhibit both of these forms of resilience on a continuum, and therefore, the strategies should account for and include varying degrees of both. For the MSIAR, these conditions or strategies will be referred to as *types* or the *typology of resilience*. Additionally, to prevent confusion with previous applications of resilience theory, these types will be referred to as *resistance resilience* and *recovery resilience*.

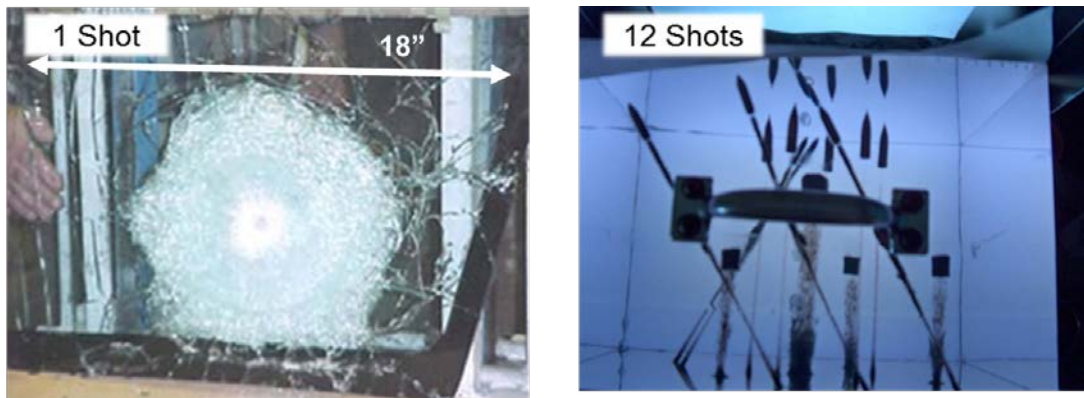
1. Typology of Resilience

As previously discussed, two types of resilience exist. The two types of resilience were previously referred to as ecological resilience and engineered resilience when used in an ecological context. In a technical context, these types are more accurately termed resistance resilience and recovery resilience.

(1) Type 1 Resilience: Resistance

Type 1 resilience, called *resistance resilience* (T1R), is characterized by the diversity and magnitude of disturbance or perturbation a system can withstand or absorb without having its fundamental behavioral structure or top-level functional state redefined. An example of a system with strong T1R is an armor panel made of steel that can withstand many hits throughout its area from a given threat projectile. As long as the threat projectile

does not hit the same location more than once, the protective capability of the armor plate is maintained. An example of a system lacking T1R is an armor panel made of glass, which may be effective against a few threat projectile hits but rapidly degrades in top-level function of protection with each subsequent hit. In contrast to Type 2 resilience, Type 1 resilience relies on adjustments to system processes or states (differing hit locations) as the means of maintaining the top-level functionality of the system (Ruhl 2011). This is graphically depicted in Figure 14.



Glass is an excellent ballistic material until it is fractured. Its armor protection capability significantly diminishes with each shot after the first strike. Further, glass armor is usually used to enable a protected viewport out of the volume that is protected. Once hit, the glass loses its light transmission capability, thus eliminating its transparency. Resistance resilient materials are being researched which mitigate the glass armor's lack of resistance resilience. The image on the right shows a polycarbonate material which has sustained over 12 ballistic impacts and still provides visual transparency.

Figure 14. Transparent Glass Armor.

(2) Type 2 Resilience: Recovery

Type 2 resilience, called *recovery resilience* (T2R), is a system's ability to reconfigure or adapt its functionality to regain equilibrium or top-level functionality. T2R typically produces a targeted response that can withstand much greater magnitude of the disturbance or perturbation that created the situation requiring system recovery (adaptation). Recovery is often associated with and measured by the amount of time required for a recovering system to regain top-level functionality. Holling referred to this type of resilience as engineered resilience because it is closely related to system

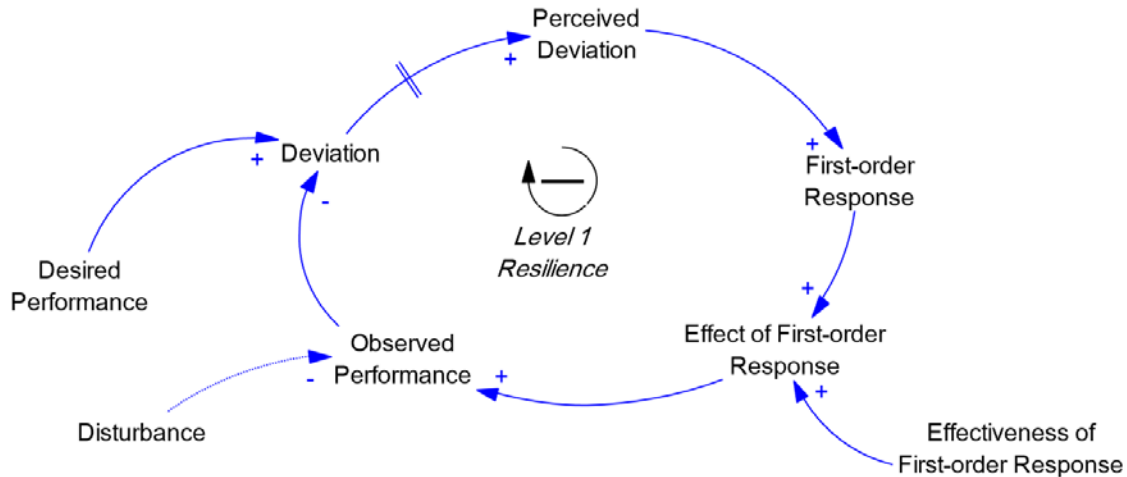
reliability, efficiency, and other engineering attributes associated with maintaining operationally effective states (Ruhl 2011).

2. Levels of Resilience

Robert Wears and Bradley Morrison (2013) proposed an interesting perspective on resilience regarding the levels of resilient systems complexity in terms of three distinct levels of complexity. These three levels of resilient systems have increasing levels of complexity and capacity that enable the systems to adapt their processes to accommodate specific challenges associated with accomplishing a function.

(1) Level 1 Resilience

Level 1 resilience (L1R) systems are associated with systems that contain a simple negative feedback loop. Figure 15 is a causal loop diagram showing how L1R systems respond to disturbances and perturbations by adapting future functional inputs based on recent operational performance outputs. The system must possess a desired zone or a state of operation output values that when violated induce a corrective response to adapt or change the system inputs to values to regain the desired output. The cruise control on a car is a simple example of a L1R system. A vehicle's cruise control set at 55 mph will increase the accelerator inputs when the car begins traveling up a hill to account for the reduced velocity and increased energy required to move the car up the hill. Conversely, the same car on cruise control will reduce the accelerator input value if the car exceeds 55 mph traveling down a hill. The top-level functional state of the car's cruise control system is to achieve and maintain a speed of 55 mph. If the vehicle exceeds this value, an L1R process is initiated to reduce the car's velocity to the desired top-level functional state. If the vehicle begins losing velocity, the L1R process initiates increased input values to the accelerator to increase the car's velocity back to the desired top-level functional state. Work associated with resilience in ecosystems typically involves L1R processes. Although the feedback loops and systems as a whole are typically more complex than the system shown in Figure 15, the fundamental resilience process driving the system adaptations are L1R systems seeking homeostasis.



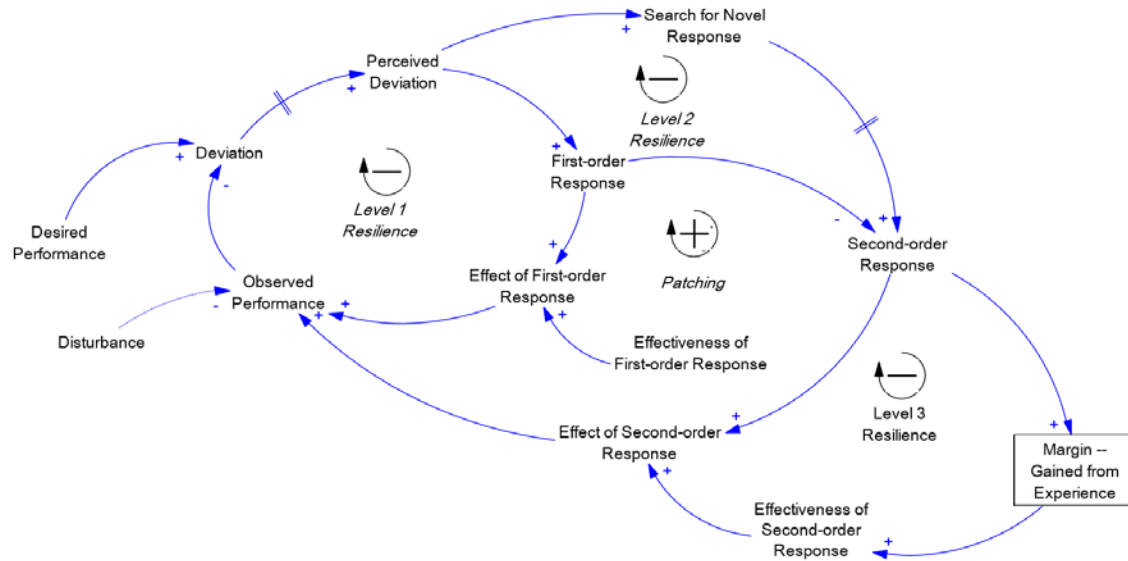
Source: Wears and Morrison (2013).

Figure 15. Level 1 Resilience Causal Loop Diagram.

(2) Level 2 Resilience

Level 2 resilience (L2R) is a second-order “novel” response to a system disturbance that addresses shortcomings or inefficiencies resulting from the L1R response. Figure 16 is a causal loop diagram showing how L2R systems respond to disturbances and perturbations. L2R responses are often characterized by variations, or novel applications, of existing processes and procedures. In instances of L2R systems, external inputs from the environment not only alter the system’s performance, but also alter the processes and sequences that influence and adapt the system’s performance (Wears and Morrison 2013). L2R systems and outputs often involve tradeoff or sacrifice decisions. Using the car cruise control example, a L2R cruise control system might invoke a response from the transmission or braking system to regain the desired speed. When the vehicle goes down a hill, an L1R system may completely remove all accelerative input from the fuel system. This response, however, may not keep the system at the desired top-level functional state (velocity of 55 mph). Therefore, the L2R system may downshift the transmission to a lower gear, which would apply the engine’s compression as a means to slow the vehicle to the desired velocity. The L2R system could also engage the braking system.

feedback, the system may then begin to learn to apply its L1R and L2R responses optimally (Wears and Morrison 2013).



Source: Wears and Morrison (2013).

Figure 17. Level 3 Resilience Causal Loop Diagram.

Means of machine and system learning include artificial neural networks, pattern recognition methods, and extensible training regimens, which continuously condition systems to learn behaviors to counter emerging perturbations. These means allow a system to self-optimize to its operating environment and store the behaviors as available system input states. These input states are then compared with the associated system output to achieve and maintain the desired or optimal system performance. When the system encounters similar external or environment circumstances, it will then base its new L1R or L2R response on its previous performance in that similar situation. Thus, the L3R response shapes and refines the L1R or L2R responses to achieve an optimal state of system output or performance. Additionally, because the system learns and stores these historical responses, the system tends to build performance margins or strategies that can be employed in rapid or extemporaneous fashion.

Continuing the vehicle cruise control system example, an L3R response could involve maintaining speed on a very rough road. A rough road could induce rapid

decelerations and accelerations that could cause the L1R and L2R of the cruise control system to engage continually and unnecessarily. This could cause the vehicle to engage or disengage the accelerator and transmission unnecessarily as it attempts to maintain 55 mph. A L3R response would recognize this rough terrain based on previous experience and perhaps disengage the L2R response on the transmission or reduce the sample rates of the feedback loop to prevent the system from fighting the terrain in attempting to maintain the desired velocity. This L3R response influences and optimizes the L1R and L2R responses that maintain the desired top-level function of the system.

C. ENGINEERED RESILIENT SYSTEMS VS. RESILIENCE ENGINEERING

Although the terms *engineered resilient systems* and *resilience engineering* sound similar, they are very different. The following paragraphs describe and differentiate each of these concepts.

1. Engineered Resilient Systems

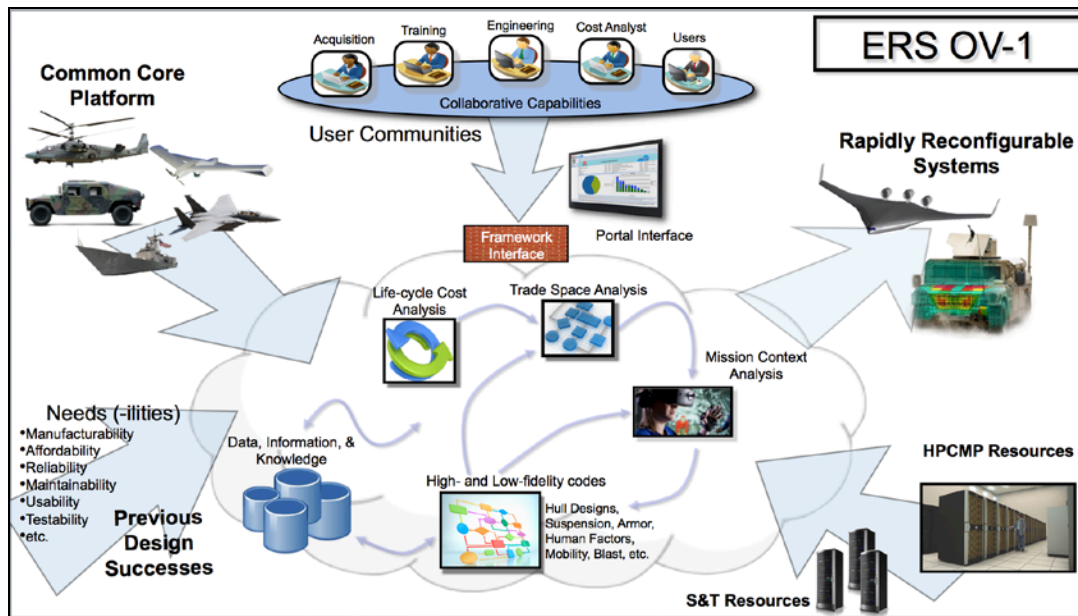
During a speech given on April 3, 2013, then U.S. Secretary of Defense (SECDEF) Hagel commented, “We need to continually move forward with designing an acquisition system that responds more efficiently, effectively, and quickly to the needs of troops and commanders in the field” (Hagel 2013). SECDEF Hagel made this statement to emphasize that defense systems were becoming more costly and technologically complicated and complex, leading to more risk in their development. Military leaders across the services and especially those in the defense-system acquisition community began investigating ways to apply the SECDEF’s verbal guidance. Subsequently, many defense acquisition agencies began focusing on engineered resilient systems (ERS). In late 2013, members of the U.S. Department of Defense (DOD) enthusiastically embraced this “new” concept and approach to the defense-systems acquisition process. According to Holland, Director of the Army Engineer Research and Development Center (ERDC), engineered resilient systems is a U.S. DOD acquisition, science and, technology thrust area in which researchers seek to generate processes, procedures, practices, and tools that will enable the defense research, development, and acquisition community to meet the vision of the former SECDEF (Holland

2013; Goerger 2013). Holland explained that the intent of ERS was to increase the speed of system development and imbue broader capability and subsequent effectiveness of fielded systems, all while minimizing system life cycle costs. Goerger, also from ERDC, claimed the DOD goals of ERS were to develop the tools and procedures within DOD acquisition process to

1. Produce more complete and robust requirements prior to materiel solution analysis
2. Make the engineering design process more efficient and effective
3. Consider the manufacturability of a proposed design explicitly
4. Establish baseline resilience of current capabilities. (Goerger 2013, 5)

As shown in the OV-1 diagram (Figure 18. ERS process architecture requires inputs from the defense platform/system program management offices, inputs from users and doctrine communities in the form of system requirements, and analysis resource inputs. These inputs are then analyzed with regard to cost, functional/performance tradespace, and mission factors. The outcome consists of system designs that are rapidly reconfigurable with respect to the needs and requirements of the operating environment (OE).

Based on analysis of the Operational View—1 (OV-1) diagram shown in Figure 18. the main difference with the existing processes and practices is the greater emphasis on prior acquisition processes and analysis to have field-ready defense system evolutions that can address predicted functional requirement changes. ERS produces the same system products as existing systems engineering and acquisition processes; however, they are supported only with a more responsive and resilient acquisition enterprise to accommodate requirement changes (Rhodes, Ross 2014). The ERS concept does not necessarily deliver a more resilient physical system.



Conclusions drawn from this ERS OV-1 suggest that the enterprise system acquisition process is what is made more resilient by the ERS concept. The result of this enhance resilient enterprise system acquisition process are rapidly reconfigurable systems, and not necessarily systems with enhanced resilience. Source: Holland (2013).

Figure 18. Engineered Resilient Systems Operational View 1.

The DOD ERS output of rapidly reconfigurable systems (RRSs) can be interpreted in many ways. In the broader context of ERS, RRSs are the result of establishing the ways and means of ERS. In other words, RRSs are the outcomes of ERS processes (the results of the integration of a common core platform, functionally successful heuristics, and the tools and resources needed to create the rapid reconfigurations) (Rhodes, Ross 2014). This definition implies that an ERS is essentially a rapid redesign or modification that occurs in protracted timelines that may or may not be faster than existing approaches to fielding system design changes. A system requirement will change, thus rendering a current system unable to achieve its functional task and requiring an engineering change to the system to enable it to regain its top-level function or task. The system must undergo an engineering change proposal and execution process. This process time and resource consuming. This requisite engineering/system process is how fielded DOD systems are upgraded and changed when requirement shift or evolve. ERS will still be subject to that same process but the tools available to solve the problem will be more suited for timely turn around.

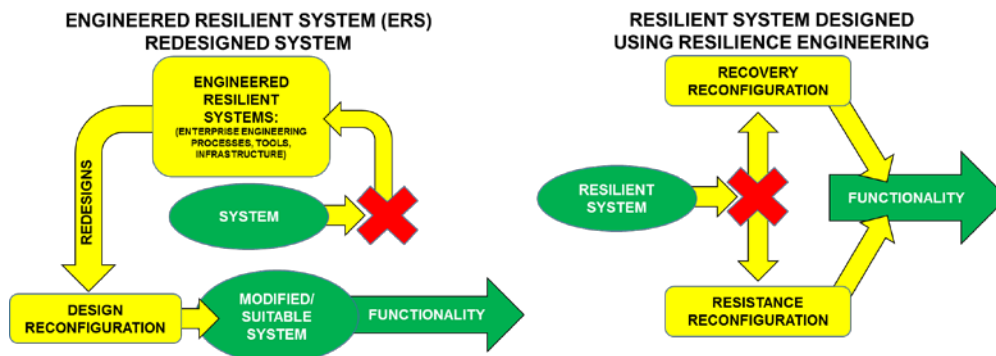
2. Resilience Engineering

The aims of system resilience and resilience engineering are the same; however, resilience engineering is different from system resilience. Resilience engineering emerged from resilience theory, a theoretical framework applied in the late twentieth century to discover how ecological systems resist or recover from environmental disasters (Holling, Allen, and Gunderson 2009). Contemporary resilience engineering is primarily applied to enterprise systems that function in complex environments—for example, emergency rooms, air traffic control, and power-grid management. Resilience engineering typically involves explicit design measures and processes built into these enterprise systems to give them robustness, yet flexibility to recover from functional disruptions that would otherwise cause the system to fail (Resilience Engineering Association 2016). System failures are an outcome of normal performance variability; therefore, a “resilient system” is able to “adjust its functionality prior to, during, or following changes and disturbances, so that it can sustain required operations even after a major mishap or in the presence of continuous stress” (Hollnagel, Woods, and Leveson 2006, 56). Adaptive resilience borrows many of the principles and approaches of contemporary resilience engineering and applies them to achieve similar ends in physical technological systems.

3. Differentiating Engineered Resilient Systems and Resilience Engineering

It is important to distinguish between engineered resilient systems and resilience engineering because these terms are increasingly confused in the systems engineering field of study. Engineered resilient systems is a DOD project designed to establish and reinforce the necessary infrastructure, enterprises, and knowledge to inform defense research, development, and technology acquisition to address the complex operating environments defense systems will encounter. Resilience engineering, in contrast, is a field of study and practice that fuses systems engineering with reliability, availability, and maintainability (RAM) engineering, risk management, and operational research (among many others) to produce physical resilient systems. In essence, resilience engineering is the operating space, or bin, for any and all activity associated with making systems, processes, and enterprises more robust and resilient, whereas engineered resilient systems is an enabling effort or

activity that will bring the resilience engineering competency to the U.S. Department of Defense acquisition process. One is the practice of building resilience in systems (resilience engineering); the other involves establishing the means to build resilience in system development processes (Engineered Resilient Systems). Figure 19 depicts this difference.



Engineered resilient systems rely on resilient engineering processes, tools, and infrastructure that rapidly enable system modifications and new system development when existing system requirements change. This is essentially the same as the recover reconfiguration shown in the resilient system-engineering image on the right. Systems developed and engineered with system resilience (right image) as a requirement are able to resist or recover from system stresses or failures through innate system configurability. This does not mean that ERS systems cannot be engineered to be resilient, but rather, the DOD ERS project does not specifically target resilient physical systems as a product, and resilience engineering does.

Figure 19. Engineered Resilient Systems vs. Resilience Engineered Systems.



D. ADAPTIVE RESILIENCE

Adaptive resilience is a system attribute which enables a system to adapt its functional traits, structure, process, and/or identity in order to maintain or regain functional effectiveness in satisfying its top-level functional requirements. The conceptual need for adaptive resilience stems from the growing complexity present in modern system operating environments. Traditional technological systems are generally developed and fielded with a set problem or fixed set of requirements that the system's functionality solves or fulfills. These systems generally operate at one optimized design point for a given set of external operational conditions to achieve a given set of principal/parent system tasks (Braha, Minai, and Bar-Yam 2006). This approach, although acceptable for most systems, presents significant functional limitations for systems required to operate or function in complex

environments where those external operational conditions are unpredictable, experience perturbation, or rapidly shift. The purpose of adaptive resilience is to enable a system to adapt its functional traits, structure, process, and/or identity in operationally relevant timescales in order to maintain or remain functionally effective in satisfying its principle/top-level functional requirements in an unknowable and rapidly shifting environment. In order to achieve an adaptive resilient system, system designers and engineers must identify, account for, and incorporate the necessary range of performance–trait adaptability or adaptive capacity early in the design and development process. Therefore, an effective integration methodology is required to achieve system-level adaptive capacity during the system design and development process.

1. Traditional System Design Methods

In the early 1990s, systems designers proposed a design methodology to map stakeholder needs to functional requirements effectively and then to map those functional requirements to physical components. The methodology was called *axiomatic design*. This methodology centered on two axioms or principles that if followed, made systems designs simple and acceptable (Suh, Crookall 1990). Only Axiom 1 will be discussed in this dissertation because it is most relevant. Axiom 1 calls for maintenance of functional requirement independence when tracing functions to physical components. In this process, the modification of physical component parameters remains isolated to the function that must be addressed. For example, consider a kitchen faucet. Imagine a user wants to control the temperature and flow rate from the faucet. A faucet with a hot knob and cold knob would require the user to tinker with both knobs with both hands to find the desired flow rate and temperature. When the sink's hot water flow function is coupled to the cold water flow function, these functions are not independent and according to axiomatic design, less desirable. In contrast, a sink with a single handle regulating both flow and temperature enables the user to singlehandedly attain the desired flow and temperature. This is depicted in Figure 20.

	<p>Designs which do not satisfy the Independence Axiom are called coupled. An everyday example is a typical water faucet. The two FRs are "control the temperature" and "control the flow rate." The two DPs are the hot- and cold-water handles. This design is coupled because it is impossible to adjust either DP without affecting the other FR: Each handle affects both temperature and flow rate.</p>
	<p>Designs which satisfy the Independence Axiom are called uncoupled or decoupled. The difference is that in an uncoupled design, the DPs are totally independent, while with a decoupled design, at least one DP affects two or more FRs. As a result, the order of adjusting the DPs in a decoupled design is important. In the above example, the two FRs- "control the temperature" and "control the flow rate" are independent. One DP does not effect the other so this design is uncoupled.</p>

This figure shows uncoupled axiomatic design using faucets. Dual-handled faucets are coupled and therefore less desirable for controlling temperature and flowrate, compared to the single-handled uncoupled faucet design. "FRs" refers to functional requirements. "DPs" refers to design parameters. Source: Axiomatic Design Solutions (2016).

Figure 20. Coupled and Uncoupled Faucets.

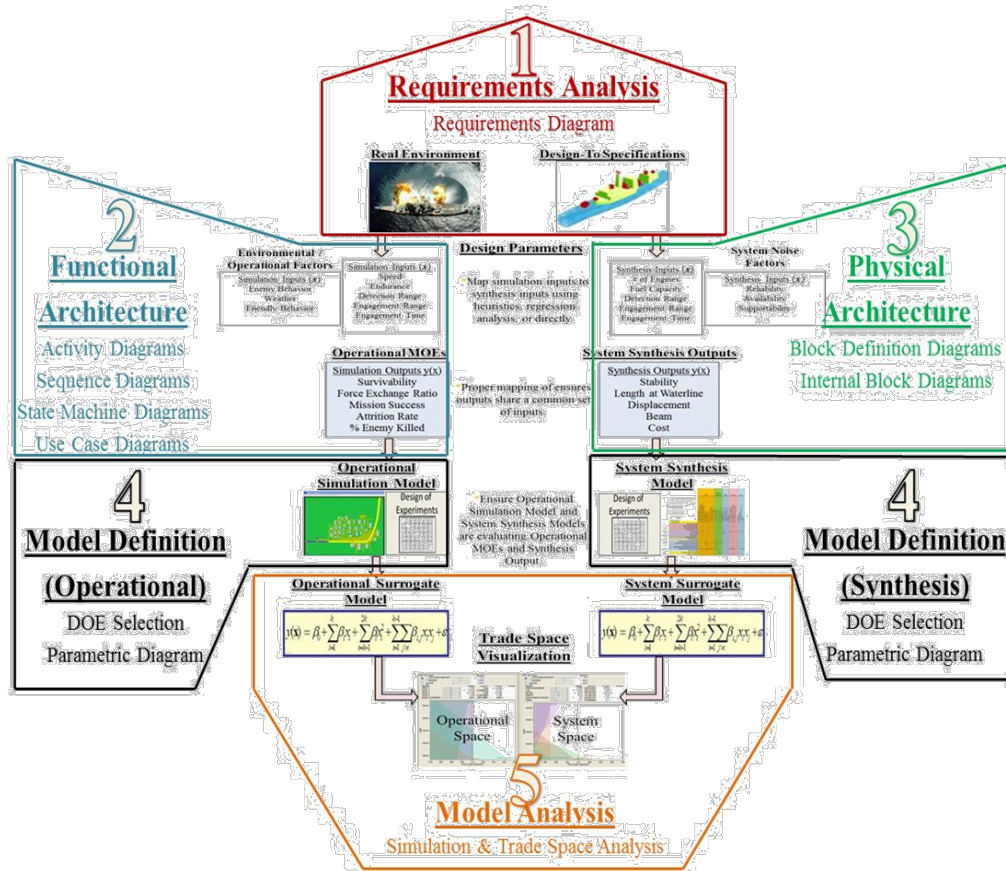
Dennis Buede (2009) further extended this concept of uncoupled design in his book *The Engineering Design of Systems: Models and Methods*. Buede claimed that the axiomatic design approach offered by Suh lacked "sufficient richness of concepts" in the process he proposed to handle the complexity in engineered systems (Buede 2009, 53–55). Buede also stated, "Suh's process does not provide a sufficient process to develop and enable validation of the requirements" (Buede 2009, 53–55). Buede proposed the use of systems engineering methods and tools to fill the gaps in Suh's process. He supplemented the hierarchical axiomatic design method with a concept called *allocated architectures* (Buede 2009, 284–290). The allocated architecture merged the functional architecture analysis and the physical architecture analysis into holistic system architecture with functions mapped one-to-one with the executing components that meet the system's stakeholder requirements. As previously discussed in Chapter I, these design methods often fail when the functional requirements shift due to uncertainty and complexity in their operating environment. The requirement that is

allocated to an optimal physical component works very well, until the requirement shifts or changes to a state that is unachievable by this optimized component.

2. Contemporary System Design Methods

Others have identified this problem and have proposed ways and means to address it. Many of these approaches focus on how the functional requirements are developed rather than focusing on resilient components which address the functional requirement. Many approaches focus on the system functional tradespace. Systems engineering is largely focused on managing the functions of a system in a way that achieves all of their outcomes with minimal collateral effects. Functions within a system often compete and affect one another. Tradespace analysis shapes functional requirements in a way that trades away competing functionality from one requirement to gain functionality from another. The aim is to strike balance between various functions, which enables some minimum level of capability in each function. The goal is to find a system design point which is functional at many design points but optimal in none. These systems from here forth will be called robust systems. The problem with robust systems is that it is difficult to understand the functional outputs and broader effects that a single function has on adjacent functions within a system (McKenney, Kemink, Singer, 2011; Doerry 2012). Taking this approach was limited as there were minimal ways for system designers to become informed on the effects of each function (MacCalman, Beery, Paulo 2016). To broaden this awareness would require excessive amounts of experimentation to build a common operating picture of a systems functional effects across its field of related functions. MacCalman, Beery and Paulo proposed low fidelity modeling approach which explores and illuminates a system's tradespace using statistical experimental design (MacCalman, Beery, Paulo 2016). This approach builds that common operating of system functions and various system design points and informs the designer on the feasibility and performance at that design point, or any other potential design point they desire to understand. This is helpful for systems which operate in uncertain environments because the designer can pinpoint a broadly applicable design where functional utility is realized in broad set of operating conditions.

Beery built on this work and generated a method that provides clear process steps and ideal tools for applying this concept (Beery 2016). Beery’s MBSE methodology, called “model based systems engineering methodology for employing architecture in system analysis” (MBSE-MEASA), appears in Figure 21.

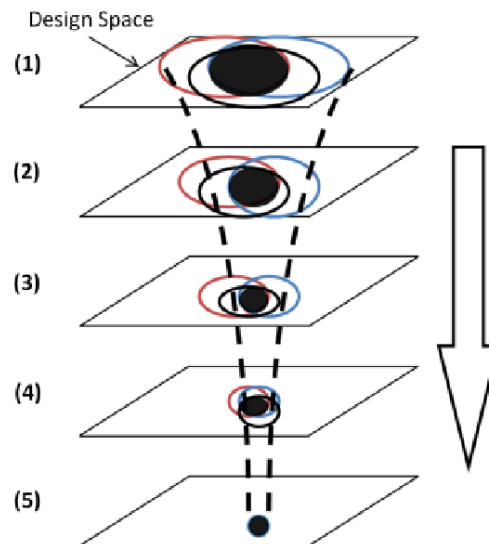


This figure depicts the MBSE-MEASA methodology, which refines axiomatic and allocated architecture approaches and provides recommended MBSE tools to clearly comprehend the system of interest using operational and physical models. Source: Beery (2016).

Figure 21. MBSE Methodology for Employing Architecture in System Analysis.

Other approaches include set based design. Set based design approaches are where system designers identify a set of functional design points that are feasible early on in the design process. The designer will then narrow the set of design points as discriminating information about the final system design become available. The final design decision is made when absolutely necessary and usually involves desired performance metrics or cost

(McKenney, Kemink, Singer 2011). By doing this, the system designer is able to make more informed decision with information that emerges as the design realization occurs. This makes the design decision more obvious and more efficient. During this time a new technology, new experiments, or just better fidelity in the final system design can emerge making the final decision or selection of the system or component design that much better. A graphic depiction of set based design is shown in Figure 22.



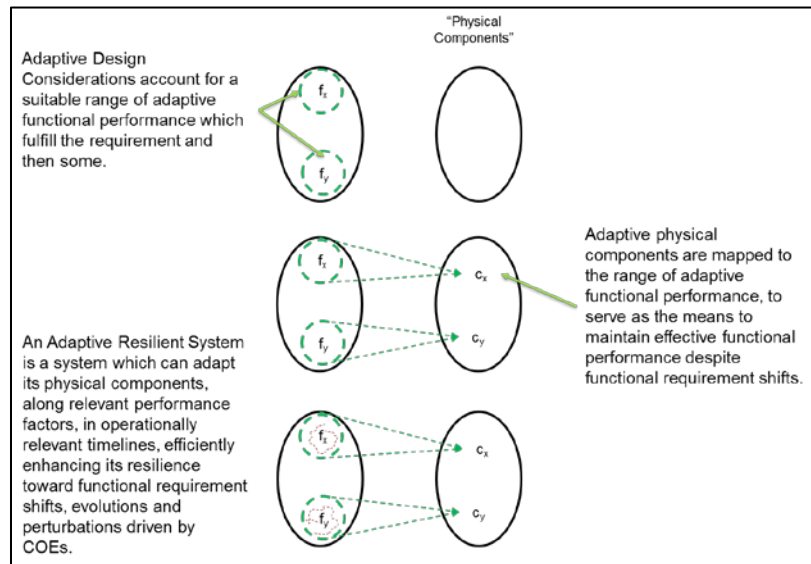
This figure depicts how set based design methodologies start with a wide set of feasible and suitable designs, and then converges on the final design when a final decision is absolutely necessary. This delayed decision time allows for greater design fidelity to be realized before constraining design decision are made; ultimately making the final system design the most informed and likely most suitable. Source: McKenney, Kemink, and Singer (2011).

Figure 22. Set Based Design: Design Space

The problem with these contemporary design approaches is that they still result in a fixed design. All of this information from tradespace analysis and delaying design decisions is helpful in making good system designs for static and uncertain environments. But the complex environment by nature makes the very most informed designs disadvantaged because the requirement will still change. A system must be able to rapidly change with the environment to be resilient to it. This is not to write off these approaches as unsuitable, just incomplete for complex operating environments. This is where adaptive resilience can take a system design to the next level.

3. Adaptive Resilient Design Method: MSIAR

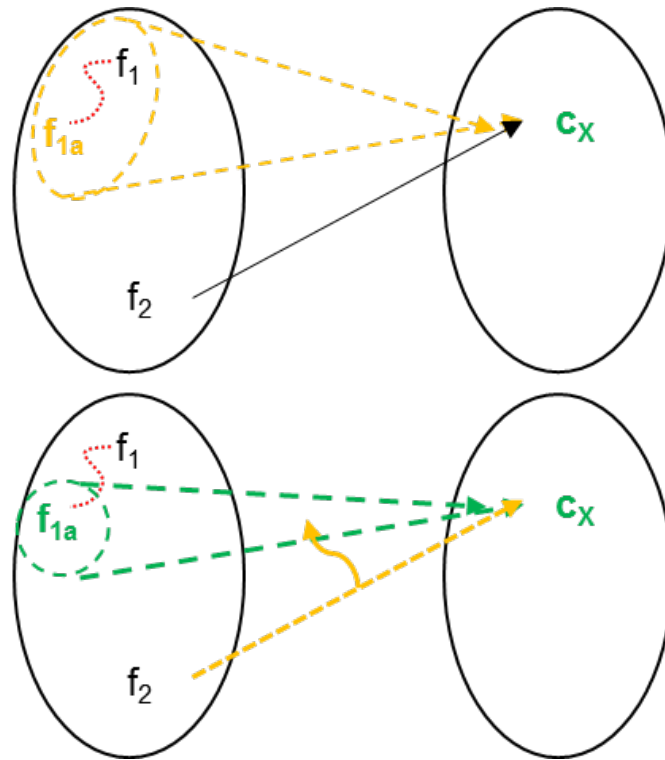
The MSIAR builds on the traditional and contemporary design methods with a supplemental design and engineering analysis intended to predict how and where functional requirements might evolve. In Chapter I, Figure 4. , Figure 5. , and Figure 6. showed high-level depictions of how adaptive resilience design is more suitable and for complex operating environments than traditional and contemporary design methods. Adaptive resilient design augments these previous design approaches. Adaptive resilience transcends the conceptual design phase where these previous approaches primarily are applied and applies this information predictively during the detailed design phase. This is not to say that the MSIAR cannot be conducted during the conceptual design phase as well. However, it must be at minimum applied during the detailed design phase. Instead of simply mapping the physical components to the functional requirement, the MSIAR methodology is designed to account for potential functional requirement shifts, perturbations, and evolutions. The MSIAR seeks to reveal where system functions could potentially evolve over a range of requirements instead of just one and then maps adaptive components capable of accommodating the functional range. This is depicted in Figure 23.



This figure depicts how the MSIAR creates a range around the functional requirement that the physical component must accommodate with component adaptive capacity. This range is predicted and accounted for during the first step of the MSIAR, defining adaptive design considerations.

Figure 23. Allocated Architecture With Adaptive Resilience.

Axiomatic design and allocated architecture push for uncoupled components in the system design. This may not always be achievable. Sometimes systems have functions that are unavoidably coupled to multiple components and components that are coupled to multiple functions. When this situation arises, MSIAR is designed to exploit this situation and bring value from that normally undesirable coupling. This concept is shown in Figure 24.



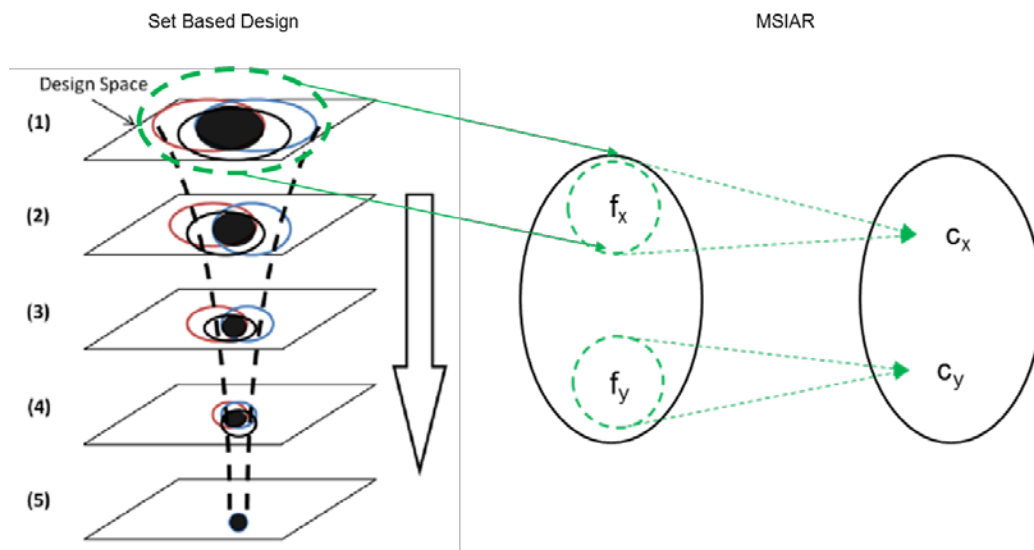
This figure depicts two functions coupled by a physical component. The MSIAR is designed to leverage functional resources from one function to provide added adaptive capacity to a component that has shifted or evolved. If the requirement shift or evolution exceeds the capacity of the adaptive physical component, the component can pull resources from another component that may not need them at that time. This can occur through the modes and means discussed earlier in this chapter.

Figure 24. Coupled Function Adaptive Resilience.

For example, a vehicle armor system adds width to its host platform. This width implicates a vehicle's mobility by limiting the vehicle's ability to traverse narrow corridors in an urban or heavily forested environment. Fixed armor width is a perfect example of parasitic capacity affecting adjacent system function. Under certain circumstances, added armor width can provide added ballistic protection. The vehicle's survivability requirements are coupled

with its mobility requirements; thus, its armor subsystem is coupled to its mobility subsystem. Under the right circumstances, these coupled systems could be adaptively traded between the subsystems to provide added capability when needed. The MSIAR would account for this through adaptive design considerations and component or subsystem means to trade away protection for mobility adaptively, and vice versa. This makes the best out of this less-than-ideal situation. This example is discussed in depth in the adaptive resilient armor case study presented in Chapter IV and Chapter V.

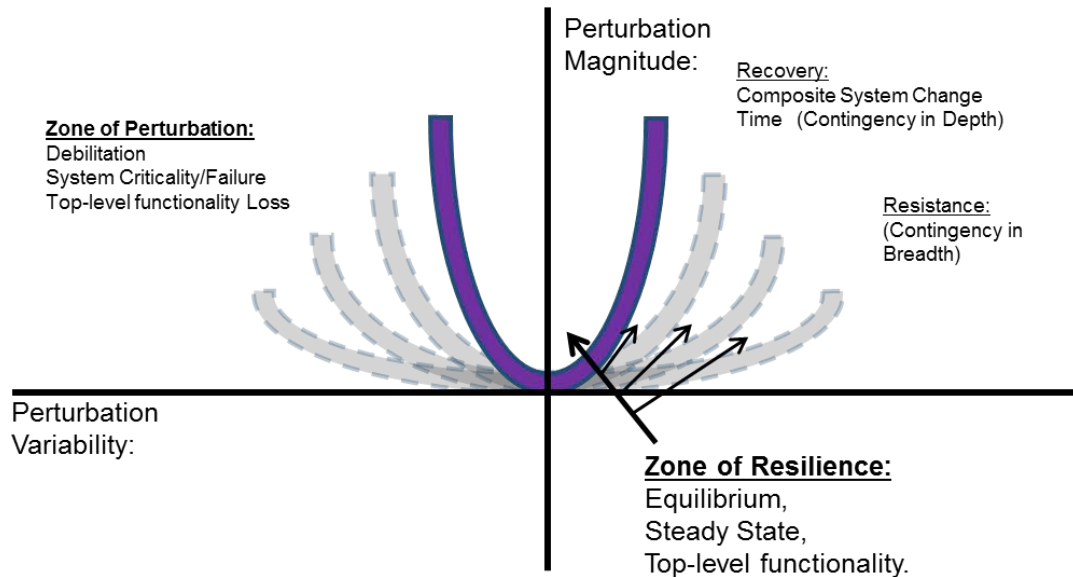
The MSIAR shares one common aspect with set based design. Where set based design identifies a set or range functional design factors and parameters to be narrowed as the system design becomes refined, MSIAR maintains this set or range. Adaptive resilience utilizes this set and seeks to find physical components which can accommodate that range of factors through internal and external reconfiguration and adaptability. This concept is graphically depicted in Figure 25.



This figure depicts how the adaptive range of consideration is closely related to the broad design sets associated with set based design. Instead of narrowing the set like set based design, the MSIAR assigns adaptive components which can accommodate this range functionality, making the system resilient to functional requirement evolutions which fall within this adaptive range.

Figure 25. Set Based Design and MSIAR

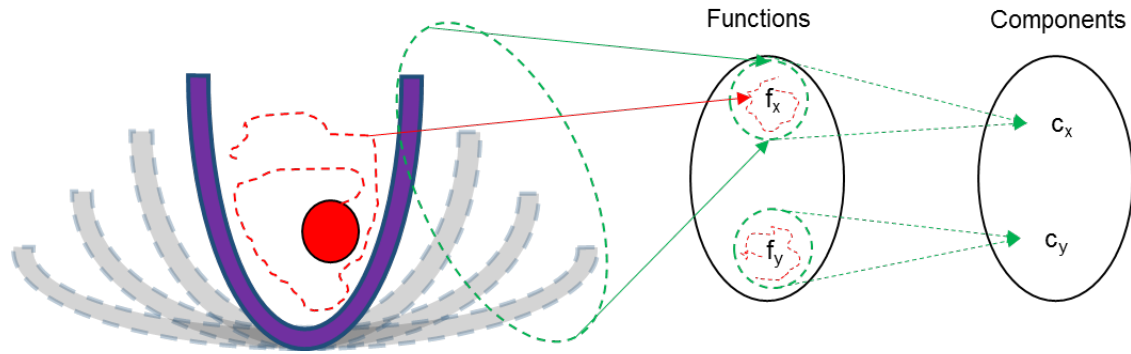
The range of functional requirement accommodation realized by the MSIAR is created when the physical system components have the necessary adaptive capacity to make that accommodation. This physical component-level adaptive capacity is shown in Figure 26.



This diagram shows the concept of component-level adaptive capacity. This capacity realizes component-level resilience (depicted as resilience basins), which provides resilience in depth and in breadth. The taller, deeper basins can handle greater magnitude of functional perturbation but indicate the component must have the adaptive capacity to reach such a state. The thinner, wider basins depict component adaptive states that can accommodate a broader or more diverse functional evolution but may lack the capacity for higher magnitude perturbations in those diverse states. Nesting the basins shows how a range of component functional states can be achieved, which makes a system adaptively resilient.

Figure 26. Component-Level Adaptive Capacity.

The purple resilience basin represents the functional state within the functional range of accommodation. The gray dash-bordered basins represent the other adaptive functional states enabled by the adaptive physical components. A visual representation linking the adaptive resilience bowls to the functional and physical component architecture is shown in Figure 27. The degrees or modes of adaptability trace to the range of functional accommodation, providing the physical components with the required range of adaptive capacity.

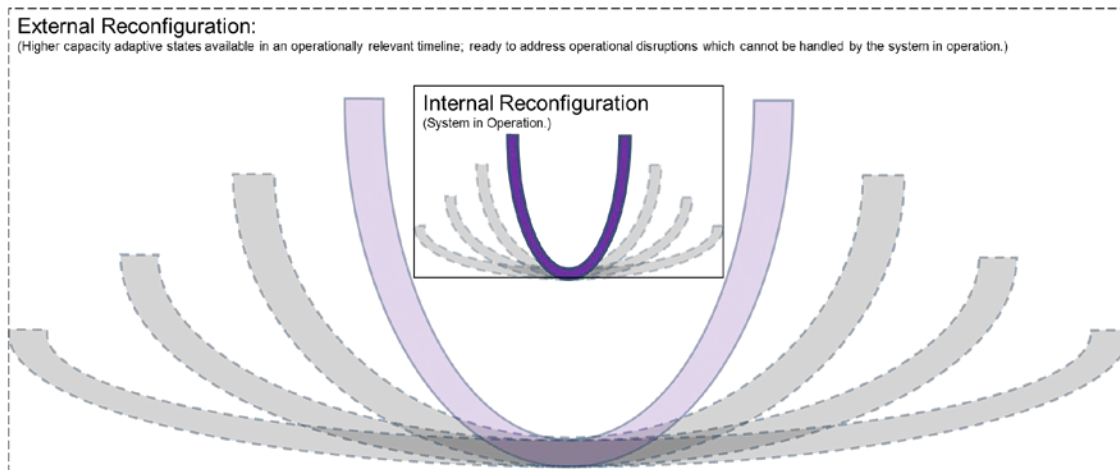


This diagram shows adaptive resilience basins as they relate to the functional range of accommodation enabled by physical components with adaptive capacity. The red ball in the adaptive resilience basin and its dashed path correlates to the functional requirement shifts and evolutions that drive the need for the MSIAR.

Figure 27. Adaptive Resilience Basins Mapped to Allocated Architecture.

E. SUMMARY OF PRIOR WORK AS IT RELATES TO ADAPTIVE RESILIENCE

In summary, an adaptive resilient system uses adaptive capacity to be resilient to functional requirement perturbations, shifts, and evolutions that would otherwise disable a system from achieving its top-level functionality. Adaptive capacity is achieved by integrating adaptive modes, external reconfiguration, and internal reconfiguration, into a system's physical component architecture. These modes are integrated into the system components by following the MSIAR when designing and engineering the system. Full system adaptive resilience, which has both internal and external reconfigurations, is depicted in Figure 28.

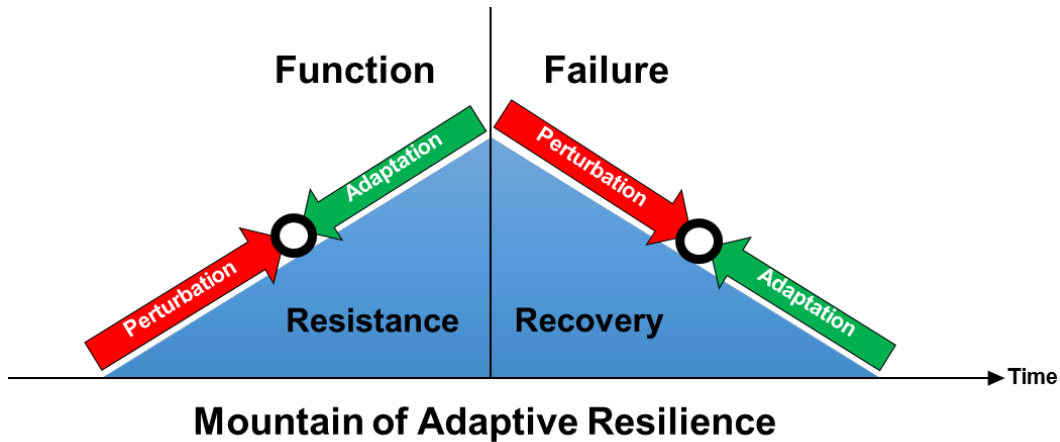


This diagram shows the concept of adaptive basins but adds external reconfiguration to the concept. Now the original adaptive basin is nested within a larger scale adaptive basin set that can be imported to the system in a rapid fashion to allow it to scale its performance to the disruption at hand. This nesting results in increased adaptive capacity.

The more nesting of internal and external reconfigurations in the system, the more degrees of adaptability are present, and consequently, adaptive resilience.

Figure 28. Nested Internal and External System Adaptive Resilience Basins.

The greater number of nested adaptive basins in a system, the higher its adaptive capacity. This adaptive capacity and capability creates the desired system resilience. This resilience has two achievable typologies: recovery and resistance. Resistance is a system's innate ability to withstand perturbations to its functionality, through either adaptation or functional robustness. Recovery is the system's ability to adapt and reconfigure itself to regain top-level functionality over time. Both resistance and recovery are achieved through the seven adaptive modes (operational variation, reallocation, degeneracy, exaptation, redundant/progressive scaling, and replace/repair/heal), each with progressively increasing timescales for employment. An alternate way to perceive the difference between resistance and recovery is shown in Figure 29.

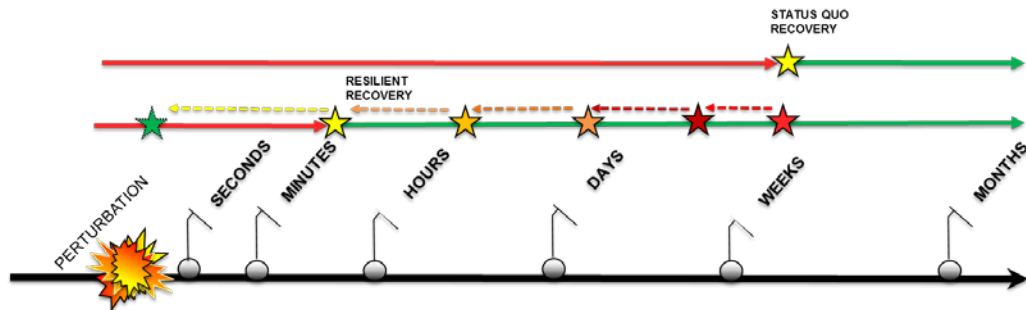


This figure shows T1R, T2R, and adaptation are the driving forces that overcome the perturbation, keeping the system on the functional side of "Mount Resilience." The system is represented by the black ball, and perturbation and adaptive forces act on it.

Figure 29. Mountain of Adaptive Resilience.

The time in which a system is able to adapt is also a critical aspect of adaptive resilience. When system perturbations and failures are encountered, the sooner the system can reconfigure itself to resist or recover, the more resilient it is. The nesting of adaptive means provides a system with multiple ways to reconfigure itself to achieve the resistance or recovery needed to resume functionality in the event of a functional requirement shift or evolution. These adaptive options often have disparate timelines for achievement. These timelines can be chronologically pursued to maintain available means and ways to regain functionality. This concept is depicted in Figure 30.

When a systems adaptive performance factors are properly nested and characterized, the system will be in a position where it can adapt optimally and agilely to the likely spectrum of functional requirement shifts and evolutions it may encounter. Additionally, the system will accomplish this by mitigating unnecessary or unwanted parasitic capacity. This enhanced state of resilience, achieved through purposeful integration of component adaptive capacity, is the system attribute of adaptive resilience. System integration of adaptive resilience is the active planning, accounting, and integration of adaptive means implemented with the explicit objective of achieving enhanced system resilience for a given physical system. The following chapter will outline the recommended methodology to realize adaptive resilience in systems which operating in complex operating environments.



This figure shows how systems lacking adaptive resilience have delayed recovery timelines to bring about lost top-level functionality. Adaptive resilient systems with multiple nested degree of adaptability can provide resistance and recovery solutions in shorter operationally relevant timelines. Operational relevance is based on how soon the system regains its lost functionality. Systems that take longer to regain this functionality are not as operationally relevant as systems that produce lost functionality sooner.

Figure 30. Operationally Relevant Timelines.

III. CONCEPTUAL DEFINITION OF THE METHODOLOGY FOR SYSTEM INTEGRATION OF ADAPTIVE RESILIENCE

A. DEFINITION OF ADAPTIVE RESILIENCE

Adaptive resilience is a system attribute that enables the system to adapt its system performance factors or parameters to maintain the ability to fulfill its top-level function and requirements in operationally relevant timescales. For example, an armor system's top-level function could be to prevent or protect against threat penetration. Nonadaptive armor systems are designed to protect or prevent penetration from a certain class or scale of ballistic threats. If a more capable threat is introduced, the nonadaptive armor system may not be able to protect or prevent penetration from that threat. If the armor cannot protect or prevent threat penetration, then the armor system has lost its top-level functional utility. Not only does the armor system lose its functional utility (first-order effect), but significant higher-order effects result from the process to correct this functional deficiency. These higher-order effects include several elements: the new requirement that engineering redesigns must account for, the cost and effort associated with that redesign, the lost operational time because of this failure, and the political/social ramifications associated with the failure of the system (e.g., death, system failure, cost). An adaptive resilient armor would be able to adapt or modify the means through which it defeated threats to maintain or regain its top-level function or requirement within an operationally relevant timeline. The system's ability to change relies on adaptive capacity accommodations made in its initial design.

1. Purpose of Adaptive Resilience

The purpose of adaptive resilience is to enable system's to maintain or remain functionally effective in satisfying its top-level functional requirements in unpredictable and rapidly shifting operating environments. The need for adaptive resilience is driven by traditional and contemporary system functional inadequacies which emerge during operation in complex environments. Traditionally, most technological systems are developed and fielded with a set problem or requirement that the system's functionality solves or fulfills. This is the top-level function. This traditional approach is acceptable for most systems, but

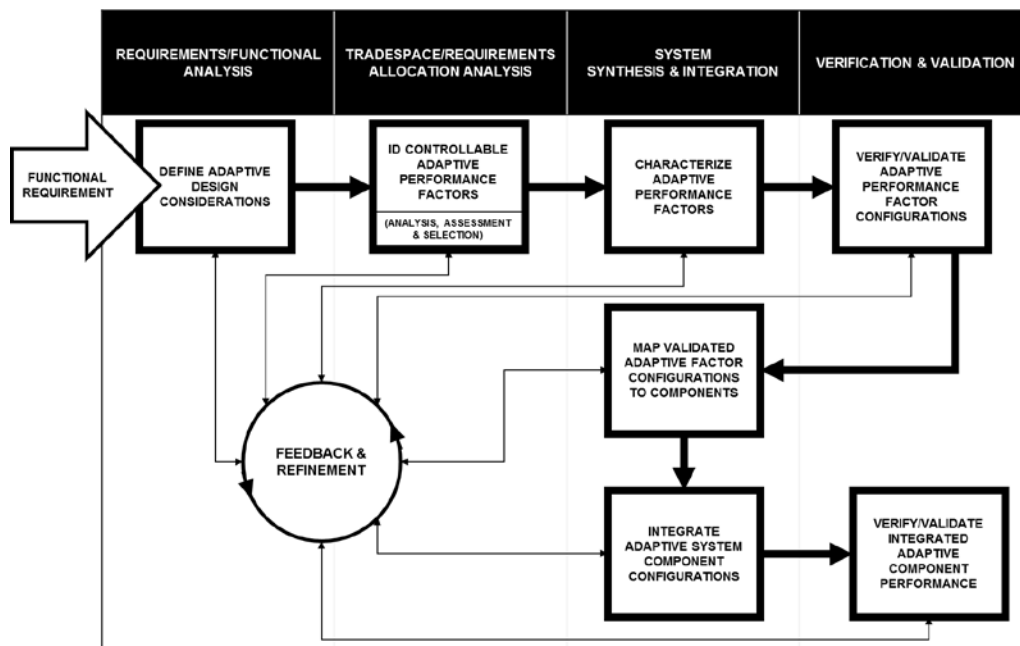
presents significant functional limitations for systems required to operate or function in complex environments in which functional requirements are unpredictable or rapidly shift. In order to achieve an adaptive resilient system, system designers and engineers must account for the capacity, range, or variability of functional traits early in the design and development process. These qualities must be integrated into the design at an early stage in the system design and engineering process. One might ask why a designer would not just design for the worst case in that range. The answer to this question goes back to parasitic capacity. Adaptive resilience mitigates undesired parasitic capacity associated with a robust fixed design. In other words, the integration of adaptive resilience enables or incorporates functional adaptive capacity within a system design, giving it the ability to agilely and efficiently change functional performance parameters in order to maintain or regain functionality with regard to a given top-level task or requirement in a broad range of complex environments or situations. However, adaptive resilience is not a silver bullet: Some limitations may hamper the ability of a system to resist and recover from disruptions, perturbations, and requirement shifts.

2. Problems Addressed by Adaptive Resilience

The key problem addressed by adaptive resilience is the limited ability of traditional systems to maintain their functional ability to maintain top-level requirements in situations with significant requirement shifts and evolutions. Armor, for example, has a principle or top-level function to prevent penetration. Armor on a military vehicle may have a requirement to prevent a small arms projectile from penetrating the exterior of the vehicle and entering the crew compartment. A traditional armor would be tested, optimized, and validated to prevent threat penetration against a statistically relevant threat scale a vehicle would likely encounter in a conflict. However, the risk remains that a light armored vehicle could face an asymmetric tactic change that renders traditional engineering and design methodologies outmoded. The asymmetric enemy has adopted complex and asymmetric tactics that are unpredictable and often emergent, employing heavily overmatched (conventional or improvised) weapons against lightly protected vehicles, as previously discussed in the prologue and introduction (Perkins, Odierno 2014). To handle these circumstances, status quo vehicles would require a significant redesign of their armor systems, requiring months of design, testing, production, and integration in order to regain

the top-level functionality of its integrated armor. This status quo engineering approach and design methodology would regain the system's top-level functionality, but again, at a singular design point, leaving the system potentially vulnerable to another rapid shift in weaponry or tactics. These types of situations call for adaptive performance capability that can resist or rapidly recover from top-level function failure. An adaptive resilient armor could be rapidly scaled along its performance factors to maintain protective capability in the event of many penetrating weapons or tactics shift (to a point). The concept of integrating adaptive resilience is intended to overcome these challenges by enabling the system to remain functionally capable with respect to its top-level function, despite requirement shifts. An adaptive resilient armor could adapt its functional attributes and tailor them in functionally relevant timelines to prevent penetration from a broad range of penetrating threats.

B. THE METHODOLOGY FOR THE SYSTEM INTEGRATION OF ADAPTIVE RESILIENCE



This diagram shows the methodology for the system integration of adaptive resilience (MSIAR). Note the binning of each process step with the generic systems engineering process steps. This methodology can be used in a stand-alone fashion or as a supplement to the systems engineering process.

Figure 31. Methodology for the System Integration of Adaptive Resilience Flow Diagram.

For many human-made systems, the ability to adapt functional performance to achieve adaptive resilience is highly desirable. A proposed method to achieve adaptive resilience is shown in Figure 31. The ability to achieve adaptive resilience is enabled by a system's innate adaptive capacity. To explain this conceptual description of this methodology, a common and relatable pickup truck system will be used. Pickup trucks generally have high automotive power and torque, but the power comes with a tradeoff in fuel efficiency. These are competing requirements that in traditional systems engineering methods would be traded or balanced away. Some days, the truck could be used to haul a heavy trailer, and on others, it could merely transport a single occupant to work and back. On the light-load days, the pickup truck provides a significant amount of parasitic capacity that detracts from desired efficiency. The daily operational requirements unpredictably shift, but shift in a way that limits the range of the shift. In an energy resource-constrained world, fuel inefficient vehicles tend to be financially costly. The ability to "adapt" a pickup truck's performance to the requisite power or efficiency need at hand would be of significant value. A highly efficient pickup truck that had the ability to change its performance configuration to achieve the needed torque and power for towing at the touch of a button would be ideal. However, how does a designer incorporate that ability to adapt into a given system? This is the question the following proposed methodology is intended to answer. The following methodology uses seven high-level steps that can be decomposed to any requisite level of fidelity for the integration effort of interest:

1. Define adaptive design considerations
2. Identify controllable/adaptive performance factors
3. Characterize adaptive performance factor configurations
4. Verify and validate adaptive performance factor configurations
5. Map validated configurations to adaptive system components/modules
6. Integrate adaptive components and configurations into system
7. Verify and validate integrated component configurations and performance

1. Define Adaptive Design Considerations

The first and most critical step to integrating adaptive resilience is defining the desired adaptive design considerations and identifying the manner in which they are adaptive. The standard pickup truck is powerful and full of utility for situations in which power and torque are needed. However, this attribute is a detractor for alternate uses of the pickup truck such as simple transportation or commuting. Driving a pickup truck 50 miles every day is on average more costly from a fuel perspective than driving a compact car. Conversely, a compact, fuel-efficient car is much less costly for commuting and simple transportation from that same fuel perspective. However, the compact car is not suitable for pulling a large trailer or hauling cargo. Another alternative would be to use the car for commuting and the truck for hauling. However, this is even more costly, because now the user must purchase and maintain two separate, costly vehicles. A potentially better option would be to have a truck that provided the power when needed, but when the power was not needed, could be reconfigured in a manner that optimized fuel efficiency and normal use costs. The existing functional requirement for the pickup truck is for it to transport passengers and a quarter-ton of cargo. However, with emerging political and environmental pressures, the pickup truck designer could employ the MSIAR and define adaptive design considerations to account for potential fuel efficiency requirements. This adaptive design consideration would be to design the vehicle to transport cargo, but with an adaptive range of performance that offered required power, optimal fuel efficiency, and every performance configuration in between. This design consideration places a range around the functional requirement that the physical components of the pickup truck must accommodate. Once the adaptive considerations are specified and applied to the existing requirement at an appropriate level of fidelity, the process advances to the next step.

2. Identify Controllable/Adaptive Performance Factors

With the adaptive design considerations applied to the requirement, the controllable or adaptive performance factors must be identified. This step enables systems engineers and designers to understand what parameters can be manipulated and adapted to achieve the desired range of adaptive performance. Functional parameters or factors are independent

attributes of a function that dictate the performance or output of that function. In an algebraic function, a factor is the independent variable (often x), which influences the dependent variable [$f(x)$ or y]. In other words, in this step of the methodology, the systems designer seeks to find the “controllable” independent performance variable(s) on which the targeted adaptive function depends. Controllable means that the factor can be manipulated easily and in an agile fashion. Controllability is critical, because if the factor cannot be controlled, then the user cannot predictably adapt it for desired performance.

In analyzing controllable and adaptive performance factors, the two modes of adaptability, internal and external reconfiguration, should be used as a starting point for ideas. In the pickup truck example, controllable performance factors are numerous. One way of quickly identifying controllable factors is to look at common components or parts and compare or contrast their differences. A pickup truck typically has an eight-cylinder engine, and a compact car typically has a four-cylinder engine. Pickup trucks generally have four or five transmission gears, whereas most fuel-efficient compact cars have five to six transmission gears. Compact cars generally have tires that have a low topographical profile for optimal friction and rolling efficiency on improved roads, whereas pickup trucks have a knobby high topographical tire profile for maximum traction on unimproved and off-road surfaces. These aspects of a vehicle can be used as adaptive factors because they are all easy to manipulate in an agile fashion. For example, shifting transmission gears is an easy adaptation of a vehicle’s functional state. However, changing the vehicle’s gear sizes and ratios is much more challenging and time intensive, making that an unsuitable adaptive factor. These are just a few obvious and controllable component or system factors related to typical pickup trucks and compact cars that directly affect the desired adaptive function range. Once the controllable performance factors are identified and specified to a desired level of fidelity, an adaptive systems designer may proceed to the next step in the methodology.

3. Characterize Adaptive Performance Factor Configurations

Performance factor solution configurations are the factor states that meet or advance the system’s performance toward the desired function performance specified in the

requirements. In other words, referring back to the previously discussed algebraic function, the performance factor solution configuration for that function is the specific independent variable value(s) that achieve the desired dependent variable values or range of values. It is the x and y combination that make the configuration. For the algebraic function shown in Equation 1:

$$i(x) = x + 5,$$

Desired Function Output : (1)

$$6 \leq i(x) \leq 8$$

What are the values of x (independent variable) that provide values of $i(x)$ that are equal to or greater than 6 and less than or equal to 8? Table 1 shows the answer and a mathematical proof of this concept.

Table 1. Algebraic Proof: Independent and Dependent Variable Defining the Functional Output within a Desired Range of Values.

x Values	Proof: $x + 5$	Function $i(x)$
0	0 + 5	5
1	1 + 5	6
2	2 + 5	7
3	3 + 5	8
4	4 + 5	9

The output values of the algebraic function are listed in the right column. These function values and input x values applied to the algebraic function serve as the function configurations for the given algebraic function set. The $i(x) = 5$ or 9 values are shown in red to denote that these values are out of the desired output range; and therefore the $x = 0$ and 4 factor values are unsuitable input configurations.

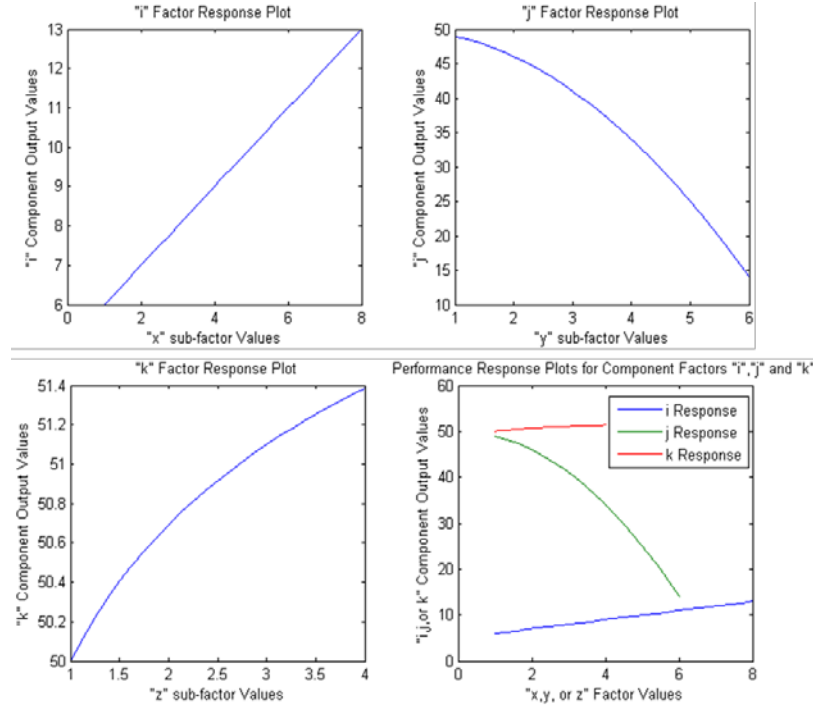
Now apply this same process to the pickup truck example. The innate system performance factors (inputs) previously identified for power and efficiency could include the number of engine cylinders, the number of transmission gears, or the topographical profile of the tire treads. By analyzing the different numbers of cylinders and by collecting data on the engine power output and fuel efficiency for each cylinder, gear, or tread quantity or state, a

linear or nonlinear function could be generated that “functionally characterizes” the cylinder count, gear count, or tread-type to the level of power and efficiency for the vehicle. Varying these factors or combinations of factors provides configurations that enable variable-dependent solutions or performance outputs (power and efficiency). Knowing how the variability in the independent factor configurations implicates the dependent performance output enables a systems designer to understand and predict how changes to the factors (gears cylinders, and treads) affect performance output (power and efficiency). Assuming that varying the number of engine cylinders has an impact on engine power and efficiency, engineers could design an engine whose number of engaged cylinders could be controlled to optimize power and efficiency for the immediate operational need.

This approach for adaptive factor characterization can be taken one (or multiple) steps further by employing multiple factors of adaptability to produce a combinatorial effect on specific functions. For example, consider the following algebraic function shown in Equation 2:

$$\begin{aligned}
 P(i, j, k) &= i(x) + j(y) + k(z) \\
 \text{or} \\
 P(i, j, k) &= \sum i(x), j(y), k(z) \\
 \text{where :} & \\
 i(x) &= x \\
 j(y) &= -y^2 \\
 k(z) &= \ln(z)
 \end{aligned} \tag{2}$$

The parent function, $P(i,j,k)$, is made up of subfunctions $i(x)$, $j(y)$, and $k(z)$. $P(i,j,k)$ represents an adaptive function output, and $i(x)$, $j(y)$, and $k(z)$ represent independent factor configuration functions. Figure 32 shows the function plots for $i(x)$, $j(y)$, and $k(z)$, as well as a combined plot for all three subfunctions.



Subfunctions $i(x)$, $j(y)$, $k(z)$, and $P(i,j,k)$ from Equation 2.

Figure 32. Performance Characterization Plots for Adaptive Factor Configurations

Now think of these subfunction plots as individual components of a system in which each subfunction independent variable is controllable, and its dependent output has direct correlation and impact on a higher-level system function. In other words, the output of the algebraic subfunctions directly translates to the functional performance of a common higher level function. In the case of the pickup truck, $P(i,j,k)$ would be the (hypothetical) power output of the pickup truck with respect to $i(x)$, which hypothetically represents the power output based on the number of engine cylinders ($1 \leq x \leq 8$). Similarly, $j(y)$ hypothetically represents the power output based on the number of transmission gears ($1 \leq y \leq 6$), and $k(z)$ represents the power output based on the tire tread profile ($1 \leq z \leq 4$). By having three configurable factors, the user has three degrees of adaptability to be able to adjust, modify, or adapt the system toward achieving the desired functional outcome and 192 adaptive design configurations along those degrees of adaptability to achieve that outcome.

Characterization of the adaptive performance factor configurations is another critical step in the MSIAR. This step in the methodology gathers the data and defines the scope of

adaptability that can be achieved for the factors of interest. The output of this step is a predictive formula that approximates the functional output of all the functional values. The individual factor outputs are not necessarily additive or linearly cumulative. It must not be assumed that the adaptive factor outputs have a cumulative effect on the overall system output. For example, changing the engine cylinders from eight to four may not integrate well with certain tire tread configurations or transmission gears. Because of this, the factor configurations and their functional outputs must be verified and validated. This is the next step in the methodology.

4. Verify and Validate Adaptive Performance Factor Configurations

Verifying and validating the resultant factor configuration solutions is critical to being able to predict accurately or even approximately the outcome of a system adaptation. Verification ensures the adaptive performance factor configurations actually achieve the desired system performance. Validation ensures that verified adaptive performance factors conform to the adaptive design considerations and system functional requirements specified in step 1. Each factor has its own effect on the adaptive functionality. Sometimes these effects are independent of the other factors, sometimes they are not. Sometimes the factors have combinatorial effects that are additive or linearly cumulative. Sometimes conflicting effects occur in which individually two factors have a positive outcome on a functional output, but when combined, have a negative outcome. Often, synergistic effects occur in which the combined output of the two factor functions is greater than the sum of the two outputs. Because of this resultant inconsistency, verification and validation of the resultant factor configuration solution must be conducted. This process generally consists of executing system tests of low fidelity system components and models at the desired characterized factor configurations. For the hypothetical pickup truck example, verifying and validating would involve testing a low fidelity prototype engine, transmission and tires at the respective various cylinder, gear, and tire tread states to acquire relative performance confirmation.

Verification and validation need not occur at each configuration state; in the pickup truck example, that goal would require 192 experiments to be conducted (8 cylinders x 6 gears x 4 tire treads types = 192 configuration points). A reduced experiment set could be

conducted to gather hard cumulative function output values with which to compare, contrast, and validate the formulaic values predicted in the previous step of the methodology. Using methods to ensure proper design of experiments (DOE), an appropriate “fractional” factorial validation experiment set could be assembled to generalize the holistic functional response at the various factor configurations. If significant discrepancies exist between the predicted functional output and the experimental output, a causal investigation could be conducted to characterize more clearly the factor correlation with the functional output. Once function outputs are verified (and potentially adjusted), the output values must be validated against the original adaptive design considerations specified in the first step of the methodology. If gaps exist between the requirements and the resultant configuration outputs, they must be filled. This can be done through further experimentation by adding additional factors, expanding the factor state range, or if the requirement cannot be met, by informing the stakeholders of the situation and proposing a change to the requirement. If the validated configuration solutions meet all the considerations, then the appropriate level of adaptability has been identified, and the conceptual system can proceed to the next step in the methodology

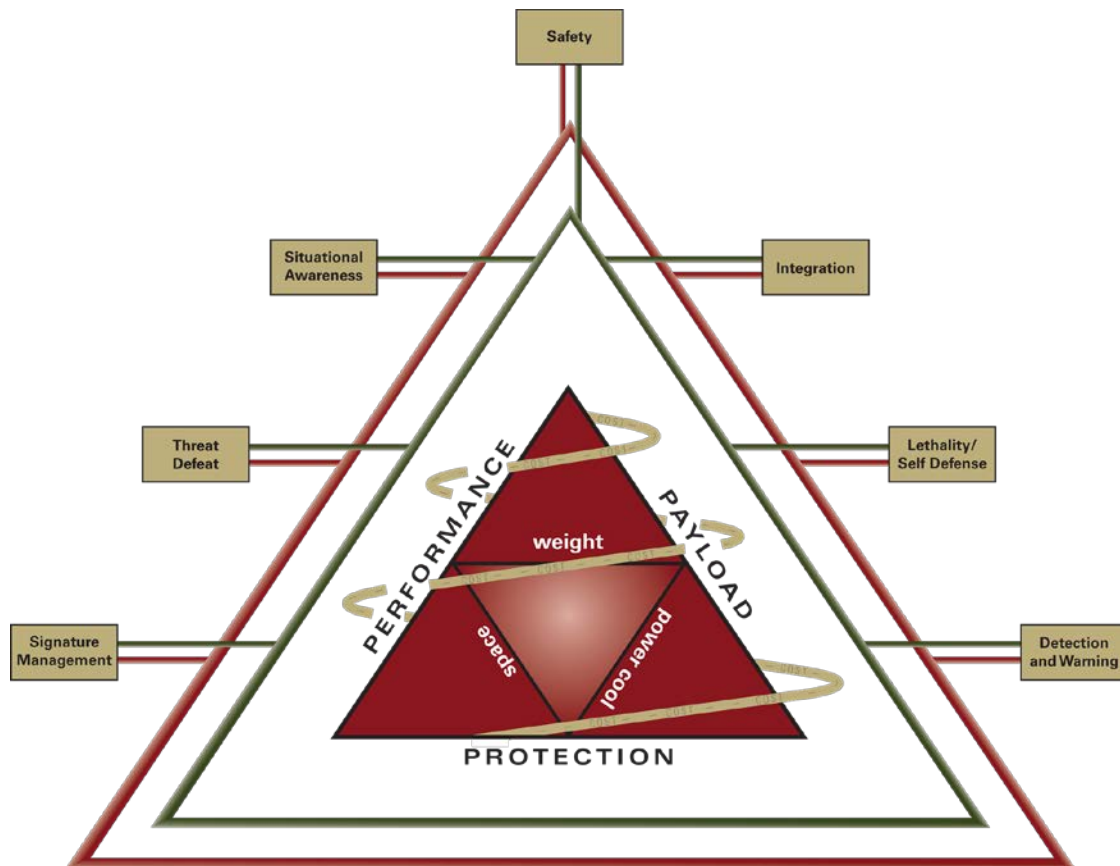
5. Map Validated Configurations to Adaptive System Components

After the configuration solution outputs have been verified and validated against the functional requirements, the next step is mapping the configuration solutions to physical subsystems and components capable of producing the configuration states and functional outputs. This step simply consists of identifying physical components that have the configurability to enable the overall system to operate at the identified configuration factor states. If subsystems or components do not exist with this capability, a design and engineering process must occur to create them or to integrate that capability into existing systems. In terms of the hypothetical pickup truck, an example of this process would be mapping the need for a V8 engine system that could turn piston cylinders on or off as needed to achieve the opposing requirements of power and efficiency (Stabinsky, et al. 2007). If an engine like this does not exist, perhaps modifying the spark plug and fuel systems on an existing engine would prevent certain piston cylinders from not firing, thus attaining the engine cylinder utilization variability number needed to achieve the dichotomous function range for engine power and efficiency. During this process, a systems designer may discover

that a physical component or subsystem cannot achieve the variable factor states or that achieving them results in unforeseen consequences that remove the incentive for having the adaptive capability in the first place. For example, turning off half of the cylinders on the engine may cause the engine to expend more fuel to drive in a normal commuter fashion, negating the desired outcome of increasing efficiency. The potential for a situation like this exists but can be avoided through the proper use of systems engineering principles. Once the mapping of requirements to components is complete, the component performance at the various factor levels must be verified and validated to confirm the predicted outcomes found in the characterization models. The characterization models numerically show what is possible and not possible regarding the adaptive performance occurring through varying factor configurations. After the systems designer identifies (or creates) the physical components, their actual physical performance must be verified and validated. This occurs in the next step.

6. Integrate Adaptive System Components and Configurations

Steps 6 and 7 of the MSIAR occur in a mutually dependent fashion. Integration cannot be complete without verification and validation, and verification and validation cannot occur unless a level of integration has been achieved. The level of integration for this step is much more in-depth, compared to the previous step, and requires analysis of overall system impacts on the vehicle. All traditional systems engineering and integration principles apply in this step of the methodology. Referring back to the pickup truck example, the integration effort might include the insertion of an adaptive engine block, a transmission, and variable tire treads into the overall pickup truck system. The integration analysis would perhaps encompass how the engine block in efficiency mode (< 8 cylinders) powers the auxiliary systems that rely on the engine for functionality (e.g., air conditioning, engine cooling). If interferences or severe implications were encountered, modifications may be required. This step is essentially the synthesis of the functional requirements with the physical adaptive components in the larger system of interest, thus ensuring that higher system performance is maintained or enhanced as desired. Figure 33 depicts an example of the integration space or tradespace that constrains ground vehicles and systems.



This figure depicts the common subsystem tradespace associated with ground systems and vehicles. The primary trades are driven by ground system performance, payload, and protection, which can be further decomposed into system attributes such as space, weight, and power/cooling. Through balancing and trading these system characteristics and attributes, opportunities, and risks emerge in the ground system survivability realm for system safety, situational awareness, threat defeat, signature management, detection/warning, lethality/self-defense, and overall system integration. This framework serves as a way to contextualize visually the relevant constraints that ground systems must manage. Adaptive resilience can help balance or even eliminate tradespace constraints for systems in which the MSIAR is applied.

Figure 33. The Ground System Iron Triangle.

7. Verify and Validate Integrated Component Performance

As in the previous step, final verification, validation, and integration occur in a mutually dependent fashion. The integrated adaptive component performance must be verified and validated against the functional requirements of the overall system. This validation and verification is for the holistic physical system. No models or simulations are used. The purpose of this step is to ensure that the physical system components are capable of physically performing at the functionally required ranges of output. Verification ensures the

integrated components actually achieve the desired system performance. In addition, verification helps characterize the performance in case there are system-level synergistic or nihilist effects from the combinations of adaptive performance factors. Validation ensures that verified integration of components conform to the adaptive design considerations and system functional requirements specified in step 1. Referring again to the pickup truck's engine cylinder variability, an engine may produce 300 bhp with all eight cylinders engaged and only 150 bhp with only four cylinders engaged. Generally, an engine that has less power output uses less fuel, but that may not always be the case. The purpose of reducing the number of cylinders engaged and having less horsepower is to increase the engine's fuel efficiency. However, what if this reduction causes reliability, availability, and maintenance issues to arise? Adapting engine size could create detrimental effects across the greater system that then must be addressed. This type of situation would be identified during this step of the methodology. This step helps ensure the adaptive functions integrated into adaptive subsystems and components physically perform and offer the desired adaptive resilient benefits for the system as a whole.

It is likely that numerous components and subsystems will be identified for factorial adaptability. However, as mentioned previously, the possibility exists that when combined, these subsystems or components could have negative or counteractive effects on the desired functional output. On the other hand, in combination, they could have a synergistic effect in which their effect on the desired functional output is positively greater. Therefore, the results of combining the adaptive components and subsystems must be compared to the original specified functional requirements and adaptive design considerations to ensure they are met or exceeded. If they are not met, then the components are likely not good candidates for adaptive resilience integration. If this is the case, the methodology must be restarted and different means of achieving the functional outcome identified and tested.

8. Summary

As with any systems engineering-based methodology, iterations and restarts of the process steps will likely occur. Feedback loops were deliberately placed in Figure 31. to denote the continual update and iteration of the steps as the user advances through the

methodology, producing new data, information, and knowledge. These insights could implicate or modify a choice or course of action selected previously in the methodology. The conceptual description of the methodology for the system integration of adaptive resilience was provided in a cursory and general fashion. Significant effort and analysis is required for each of these steps. A more detailed dive into the methodology appears in the case study in Chapter IV.

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IV. CONSTRUCTIVE IMPLEMENTATION OF THE ADAPTIVE RESILIENCE SYSTEM INTEGRATION METHODOLOGY

A. ARMOR TECHNOLOGY PRIMER

Armor, in the classic sense, is generally associated with combat or protection from an attack. The general purpose of armor is to prevent the penetrating blows of weapons, teeth, or the environment from piercing a vulnerable area. It is very likely that nature inspired the first implementation of armor by a human, perhaps prompted by an early human's witnessing of a jackal's attempt to devour a turtle on the Mesopotamian plain. The survivability/protection function of armor has existed everywhere for billions of years, tracing back to the functions of the outer membranes on the first mitochondria (Cooper 2006). Armor serves many functions, from callus tissue padding on feet to windshields on cars to the ballistic shields commonly associated with vehicles or bodies. Like armor in the nonmilitaristic sense, vehicle armor is a mature function, and the physical performance potential of this technology is at or rapidly approaching its known physical performance limits. Yet, the existing and emerging threats facing armor technologies trends toward increased penetration and lethality. Further, the entities that employ these threats are random and opportunistic in their means of employing those threats (Burns 2008). This fact has created many challenges for the classically designed armor systems utilized in the contemporary operating environment. The current and future operating environment is and will continue to be chaotic or complex (Perkins, Odierno 2014). Armor is considered a parasitic system because it serves only a single purpose and is usually heavy and burdensome, hindering its host vehicle's automotive performance and mobility. A solution to this problem would be the creation of an armor with a broad, high-performing ballistic performance, successfully deflecting the myriad threats on the battlefield, yet also achieving orders-of-magnitude less weight to avoid implicating the host vehicle's functionality. The problem with this solution is that the fundamental performance factor that drives armor performance is also the factor that makes armor so heavy—mass.

1. Common Armor Materials

In the vehicle armor domain, armor materials generally fall into two categories: opaque and transparent. Opaque armor materials are used for armoring the hulls, doors, and roofs of vehicles. Transparent armor materials, generally glass, are used for armoring vehicle windows. Opaque armors are opaque because there is no need to see through them. The most common materials for opaque armor are steel and aluminum. Numerous military specifications exist for steel armor, but two steels—MIL-DTL-46100 and MIL-A-12560—are most commonly used for modern armor applications. These two steels are commonly referred to as high-hard steel and rolled homogenous armor (RHA) steel, respectively. These armored steels are both hard yet considerably resistant to the shock sustained during high velocity impact. Both of these steels are produced by rolling cast steel billets into plates of specific thickness. Aluminum is another common armor material, used when weight savings are required. Aluminum is a very effective lightweight armor material (Gooch, Burkins, and Squillacioti 2007). Of the different series of aluminum, the most common are the 5000 and 7000 series, specifically MIL-DTL-46063H (7039-T64); MIL-DTL-32262 (6061-T651); and MIL-DTL-46027J/46083D (5083-H13; Gooch, Burkins, and Squillacioti 2007).

Common composite materials used for armor applications consist of S2 fiberglass and E fiberglass. These two materials have great toughness in addition to their high tensile qualities. A recently developed composite material used in armor applications is ultrahigh molecular weight polyethylene (UHMWPE). This material derives from the same molecular material as plastic trash and grocery bags. The difference is that this material is formed into fibers and compressed to precise processing and treatment standards, which imposes extreme pressures and heat to make monolithic sheets or blocks suitable for armor use. UHMWPE is a lightweight, high-performing material in the context of terminal ballistics. The material's main drawback is that it is prone to catching fire during ballistic events (Korobeinichev, Paletsky, Kuibida, Gonchikzhapov, Shundrina 2016). This attribute can be mitigated through chemical treatments and additives. The final opaque material commonly used in armor applications is ceramics. Ceramics have extreme hardness but generally low toughness. However, the hardness and density of ceramics makes this material ideal for armor

applications. Its main shortcomings are that it shows poor performance after an initial strike, and the material is costly.

Windows or view ports in armored vehicles have always been vulnerable points. With the emergence of the IED threat, the Soldiers operating in combat environments requested greater visual situational awareness to detect and hence prevent IED ambushes. With this request came the inherent viewport vulnerability, which led to increased efforts to develop windows and view ports with ballistic protection capability. The most commonly used material in transparent armor is glass, more specifically, borosilicate glass. This type of glass is produced in the same fashion as the Pyrex cookware glass that many people use in their kitchens (Goodfellow Ceramic & Glass 2013). Borosilicate is used because of its resistance to thermal expansion. Borosilicate glass has a thermal coefficient of linear expansion of $3.3 \times 10^{-6} / \text{C}^\circ$. Glass used in ballistic application must be very thick. This has implications in situations of temperature changes in cold and hot environments. The inside of the vehicle is heated while the outside is cold, or vice versa. The thicker the glass, the greater the temperature gradient that can occur from the inside to the outside of the panes. This difference causes thermal expansion and contraction in a material that does not have tolerance for either. Borosilicate, though not impervious to temperature changes, is more resistant to the subsequent fracture that often occurs with other glass materials in temperature extremes (Goodfellow Ceramic & Glass 2013).

Other transparent materials include polycarbonate and ceramics. Polycarbonate is an extremely tough material that is virtually impossible to shatter. Its only drawback is that it tends to scratch easily. It is often used as an interpane material between borosilicate glass sheets. Transparent ceramics is a new emerging material in the armor field. This class of ceramic material is called *spinel*. Spinel is still immature in its consistent manufacturability for transparent armor use (Weins 2015). It also extremely expensive in its transparent state. However, this material has shown great potential for ballistic performance, on par with steel.

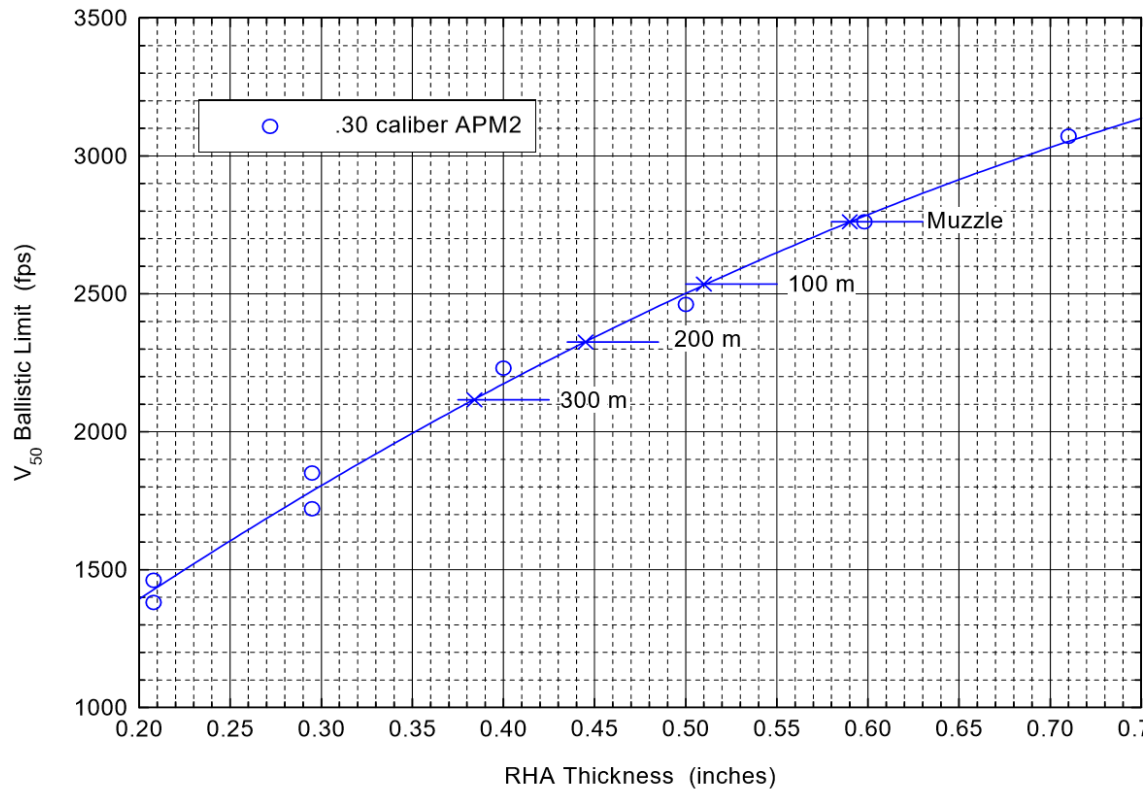
2. Armor Velocity, Mass, and Volume Metrics

a. *V₅₀ Ballistic Limit*

The ballistic limit of an armor is typically expressed as the V_{50} ballistic limit. The V_{50} ballistic limit referred to in this dissertation is the U.S. Army's criterion. The U.S. Army V_{50} criterion is a more stressing version than the U.S. Navy criterion. The U.S. Army criterion defines a complete penetration if the projectile hole would allow light to pass through to the nonstrike face side of the armor. The U.S. Navy criterion requires the entire projectile or a major portion of the projectile to have passed through the armor plate of interest (Army Test and Evaluation Command, 1984). This metric is a valuable measure of an armor material's ballistic performance. The V_{50} ballistic limit is measured by maintaining a fixed thickness and obliquity of an armor material target while a series of threat projectiles are fired at it with increasing velocities (Army Test and Evaluation Command 1984). The intent of varying the velocity is to find the exact velocity at which 50 out of 100 projectiles transition from complete to partial penetration through the armor plate. This distribution normally follows a cumulative normal distribution. After a statistically significant number of shots have been fired, mean velocity for V_{50} and the standard deviation can be determined. The V_{50} ballistic limit curve for a .30 cal APM2 against various RHA thicknesses is shown in Figure 34.

b. *Areal Density*

Areal density (AD) is a common mass measure or characteristic of an armor technology used for quick weight comparison of similar armors. In the United States, areal density is usually referred to in English units as pounds per square foot (psf). Many armor technologies use a composite or laminate construction of different materials. These materials each have a separate purpose or function and generally vary significantly in density. As a way to summarize the overall density of the armor, a 1-foot by 1-foot areal cross-section is taken of the entire armor composite and weighed. The total weight of the 1-foot by 1-foot section is the armor's areal density (Burns 2008). Table 2 shows the areal density of rolled homogenous armor (RHA) steel at various thicknesses. Using this data, an armor technology made of 1-inch RHA would have an areal density of 40 lbs.



This figure depicts the V_{50} ballistic limit for RHA plate at thicknesses ranging from .20" thick to .75" thick vs. .30 cal APM2. For example, an RHA plate at approximately .60" thick has a V_{50} equivalent to the standard muzzle velocity of the .30 Cal APM2. Muzzle velocity is the mean velocity measure of a projectile as it departs the muzzle or barrel of the weapon that is firing it, in the munitions standard load manufacture. Source: Gooch and Burkins (2004).

Figure 34. V_{50} Ballistic Limit vs. RHA Thickness for .30 cal APM2 armor piercing projectile.

Table 2. Areal Densities for Varying Thicknesses of RHA Plate.

Material: Rolled Homogenous Armor				
<u>Metric Density</u>	<u>Imperial Density</u>	<u>Thickness</u>	<u>Thickness</u>	<u>Areal Density</u>
kg / m ³	lb / ft ³	Inches	ft	lb / ft ²
7830	488.592	0.065	0.005416667	2.65
7830	488.592	0.125	0.010416667	5.09
7830	488.592	0.1875	0.015625	7.63
7830	488.592	0.25	0.020833333	10.18
7830	488.592	0.3125	0.026041667	12.72
7830	488.592	0.375	0.03125	15.27
7830	488.592	0.4375	0.036458333	17.81
7830	488.592	0.5	0.041666667	20.36
7830	488.592	0.625	0.052083333	25.45
7830	488.592	0.75	0.0625	30.54
7830	488.592	0.875	0.072916667	35.63
7830	488.592	1	0.083333333	40.72
7830	488.592	1.25	0.104166667	50.90
7830	488.592	1.5	0.125	61.07
7830	488.592	1.75	0.145833333	71.25
7830	488.592	2	0.166666667	81.43

Mass and volumetric efficiency are valuable measures of how well an armor utilizes its mass or volume, respectively, in defeating a threat. The efficiency is based on the benchmark armor material RHA. The table shows the areal density for different thicknesses of rolled homogenous armor (RHA). For RHA, the areal density is just over 40 lbs., as shown the fifth column, at the 1-inch thickness row. Areal density is a great measure and tool that assists in the comprehension and benchmarking of mass and volumetric efficiency.

c. *Mass Efficiency*

Mass efficiency (E_m) is the measure of how the armor's mass performance compares to an equivalently performing armor made of solid RHA (Burns 2008). As discussed previously, RHA is an effective but extremely heavy armor material. When dealing with armor, the ever-present battle is to minimize weight while improving ballistic performance. RHA is a default or benchmark armor material; therefore, it is used often in comparisons of armors. This measure is complicated but important in understanding how well an armor performs. Mass efficiency is calculated by shooting the armor-of-interest with a given threat to measure unpenetrated, residual-thickness areal density. That areal density is then subtracted from the given areal density of the same threat's overall penetration into RHA.

This difference is divided by the overall areal density of the armor-of-interest. This measure is formulaically represented in Equation 3.

$$E_M = \frac{(AD_{P_{RHA}} - AD_{P_{RES}})}{AD_{P_{TARGET}}}$$

where :

$$E_m = \text{Mass Efficiency} \quad (3)$$

$AD_{P_{RHA}}$ = Areal Density for Threat Penetration of RHA

$AD_{P_{RES}}$ = Areal Density for the Residual Unpenetrated Portion of the Target

$AD_{P_{TARGET}}$ = Areal Density for Threat Penetration of the Target

d. Volumetric Efficiency

Volumetric efficiency (E_v) is the measure of how well the armor uses the volume it takes up in defeating the threat (Burns 2008). This efficiency measure is calculated by subtracting the overall depth of penetration (DOP) of the threat into the armor from the threat's depth of penetration into RHA. This difference is then divided by the overall thickness of the armor-of-interest's profile. Armors that stop threats halfway into the thickness of the armor obviously perform well, but do not make efficient use of the overall armor volume (parasitic capacity). That left-over distance could be considered weight that could be trimmed off the armor or as a safety buffer in case of an anomaly in the threat performance. This measure is formulaically represented in Equation 4.

$$E_V = \frac{(DoP_{RHA} - Th_{RES})}{Th_{TARGET}}$$

where :

$$E_v = \text{Volumetric Efficiency} \quad (4)$$

DoP_{RHA} = Threat Depth of Penetration into RHA

Th_{RES} = Thickness of Unpenetrated Residual Target

Th_{TARGET} = Thickness of Target

3. Basic Penetration Mechanics

Very high velocity projectile penetration can be simply approximated through Equation 5:

$$P_{\text{Depth}} \approx L_{\text{Projectile}} \left(\frac{\rho_{\text{Projectile}}}{\rho_{\text{Target}}} \right)$$

where :

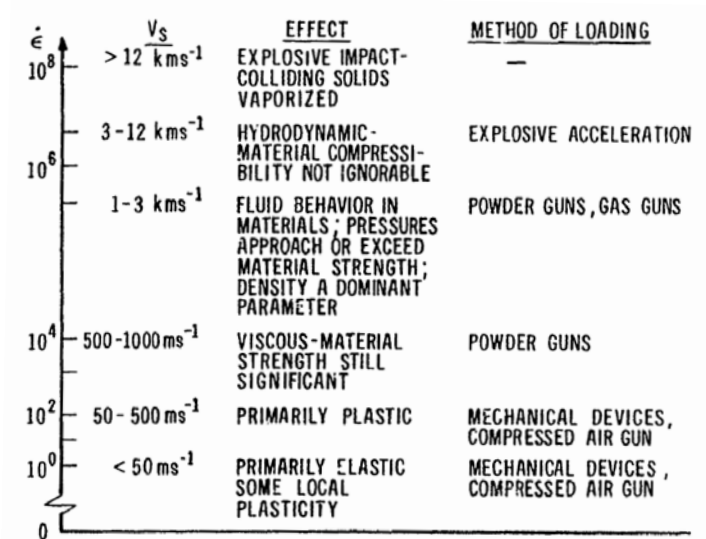
$$\begin{aligned} P_{\text{Depth}} &= \text{Penetration Depth} \\ L_{\text{Projectile}} &= \text{Projectile Length} \\ \rho_{\text{Projectile}} &= \text{Projectile Density} \\ \rho_{\text{Target}} &= \text{Target Density} \end{aligned} \tag{5}$$

Sir Isaac Newton derived this approximation, based on his observations of momentum transfer. This approximation does not take into account projectile shape, kinetic energy dissipation, target/projectile failure modes, and their associated material properties, which also play a significant role in resultant terminal ballistics. This approximation also assumes that the target is a semi-infinite block of material that can never be completely penetrated. To include a comprehensive equation that accounts for all of these factors is not appropriate for an armor primer that aims to familiarize those new to this field. This approximation is a helpful and simple way to generalize and compare the penetration capabilities of projectiles and penetration resistance from the mass of target materials. A bullet of length 1 and density 1 will approximately penetrate a distance equivalent to its length into a semi-infinite target block with density 1 at very high velocities. For conventional small arms, the projectile lengths are generally less than 2 inches. Therefore, a monolithic armor of equal density must be at least 2 inches thick to be able to stop the projectile. If the projectile and target material were steel, it would require at the very minimum 2 inches of contiguous steel to stop the projectile. To put this into the context of mass and area of protection, a 1-foot by 1-foot by 1-inch plate of steel weighs 40 lbs. This dimensional measure, as described previously, is known as areal density. The areal density required to stop the 2-inch steel projectile would be 80 pounds per square foot (psf). To continue this areal density context, assume the area for the side crew compartment of a

typical tactical vehicle is 6 feet long by 4 feet tall, or 24 square feet. To provide crew protection for this tactical vehicle, the armor for just one side would weigh almost one ton. This quick analysis demonstrates that armor technology is very heavy. The 2-inch threat is considered small compared to some of the more lethal 2 foot long (or greater) penetrating threats. To protect against a 2 foot long penetrating threat would require 12 tons, or 24,000 lbs., of parasitic armor weight, hanging on just one side of a vehicle. It should be obvious that this extreme amount of weight is unacceptable for the protection of one side of a vehicle. The only way to reduce this armor weight for such threats is to increase the complexity of armor designs.

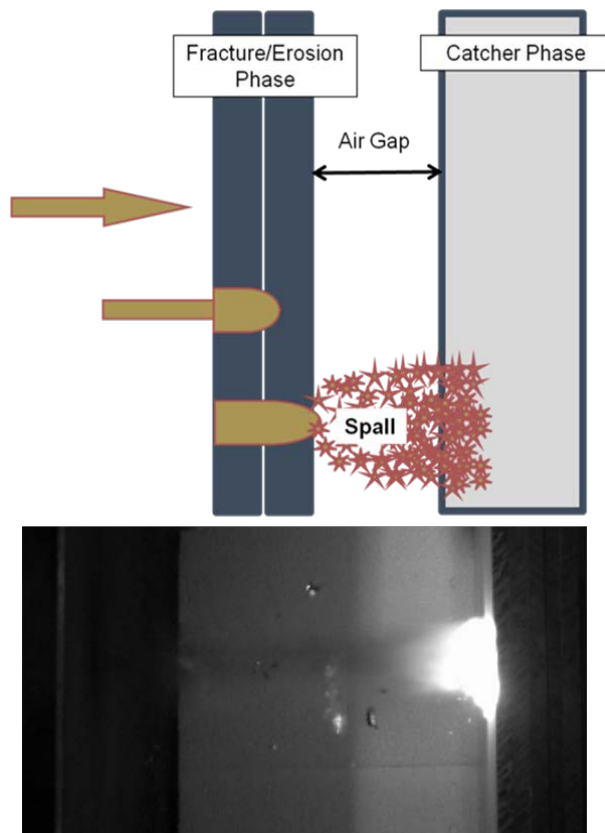
4. Static Armor Defeat Mechanisms

Contiguous or monolithic armors are the simplest form of armor in the sense that they do not employ dimensional or dynamic effects to enhance their terminal ballistic capability. These armors utilize modes of armor material plastic deformation, shown in Figure 35, to terminate the threat projectile.



This figure shows the various impact velocity regimes and their associated effects on a target. Note that as velocities break above 1000 m/s, the target material properties begin to lose significance, and the mechanical interaction between the projectile and material becomes fluid-like. Source: Zukas (1980).

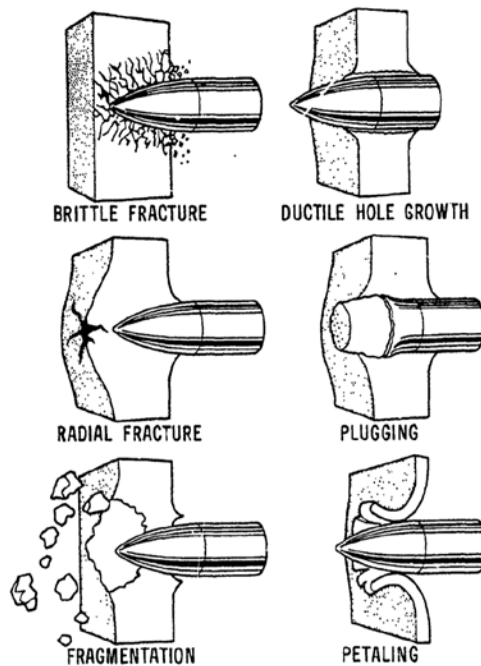
Figure 35. Impact Velocity Effects and the Method of Loading to Achieve such Velocities.



Spaced armors employ air gaps to allow fragmentation or spalling to occur. The spalling absorbs energy and disperses the projectile kinetic energy over a greater area on the second phase of the armor. The air gap acts as an expansion zone, allowing the spall to expand an impact over a greater area on the second phase of the armor, often called a “catcher.” This can be seen in the picture below the drawing.

Figure 36. Spaced or Air Gap Armor

When monolithic armors fail, the vehicle occupants they protect often face a worse situation as the armor becomes a projectile, in addition to the threat or fragment. This was a common problem in early armor technology. With the conservation of energy, these failure modes can be put to good use. Modern armors generally employ air gaps between materials to capitalize on the material failure modes of spalling, plugging, and fragmentation (Zukas 1980). Common armor material failure modes are depicted in Figure 35 and Figure 37.



This figure shows the various target or armor failure modes. These modes are highly dependent on the material of the target, the material of the projectile and the velocity upon impact. Source: Zukas (1980).

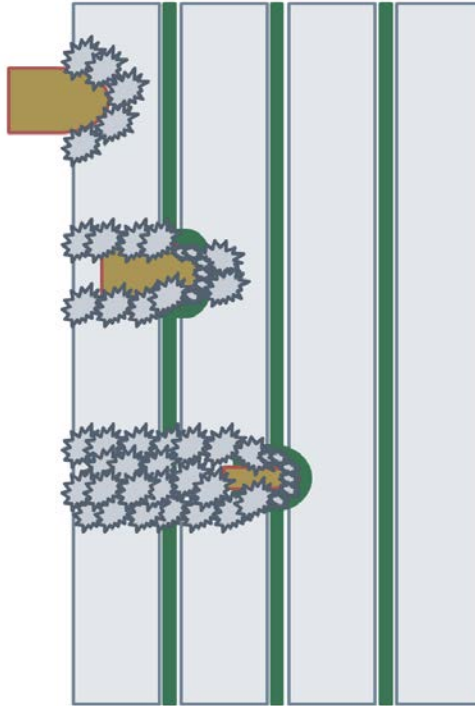
Figure 37. Common Armor Material Failure Modes.

When these failures occur, the initial energy of the projectile is dissipated in the fracture of the armor materials and in the subsequent projection of the fragments. Instead of one acute, high-energy projectile to defeat, now several larger, lower energy projectiles are spread over a larger area. These particles are generally easier to deal with than the previous pristine projectile. This modern armor mechanism is known as *spaced armor*. The most common spaced armors generally employ a very hard material (e.g., steel, ceramic, glass) to fracture and erode the projectile, dissipating its energy. The fragments of the projectile and the armor material now travel through the air gap, where they disperse the residual energy over a larger area and into the next phase of armor materials. The larger the air gap, the greater the dispersion of threat and armor particles over a larger area, reducing the penetration of the threat (Hurlich 1950).

This secondary phase is often called the *catcher* material. This material is generally softer but with higher ductility and tensile strength (e.g., aluminum, S2 Fiberglass, aramid

fibers, UHMWPE). Beyond this general concept, the only major differences between opaque armors are the selection of materials and the order, arrangement, and dimensions of their designs. Transparent armors use a similar mechanism for the defeat of ballistic projectiles, but the catcher phase of the armor is integral to the effector. Because the use of a traditional catcher armor would eliminate the occupant's ability to see out of the transparent armor, the solution generally relies on the rapid erosion and dissipation of the projectile's energy in the armor. When glass or ceramic shatters from ballistic impact, every crack acts as a sponge, or sink, for kinetic energy from the projectile. This is one of the features that makes glass an outstanding ballistic material. The other valuable terminal ballistic property of glass or ceramic is the volumetric expansion of the material after fracture. This is known as *bulking* in the terminal-ballistics community.

The thousands of jagged edges from the shattered glass/ceramic prevent the material from compacting to its original volume. This bulking can be contained by placing high toughness materials (integral catcher) between the transparent panes of glass or ceramics. Polycarbonate is used for this purpose. The polycarbonate contains this expanding volume of glass while simultaneously compacting it into a tight volume that the projectile must pass through. As shown in Figure 38, the projectile passes through this shattered glass or ceramic and is subsequently eroded to an ineffective mass. Ballistic glass and ceramic both possess impressive capacities to defeat ballistic threats; however, they do have some ballistic drawbacks. For example, both materials tend to be more expensive, not only to purchase but also to integrate, because they are brittle materials that must be insulated from the vibration and shock transmitted from the vehicle. Additionally, these materials tend to have poor multiple-hit capabilities—the panes generally shatter upon impact. Current research efforts are in progress to localize the damage and increase the multiple-hit capability of these two materials. Ceramics and glass have been employed in opaque armors to capitalize on this erosive bulking mechanism. Large panes are generally not used to prevent the shattering. Instead, geometric tiles generally smaller than one inch are used to minimize the damage zone.

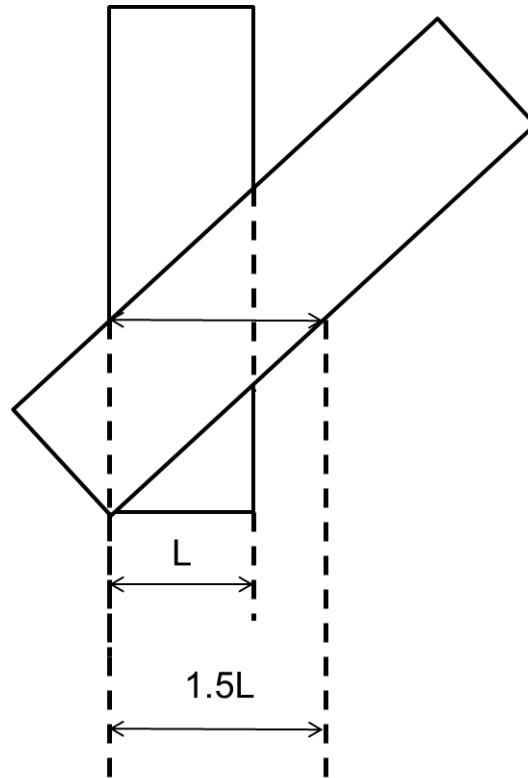


This drawing shows the bulking and volumetric expansion of glass. The green lines represent the interpane polycarbonate sheets that expand and contain the fractured glass, forcing greater erosion of the projectile. Adapted from Grujicic, Pandurangan, Zecevic, Koudela, and Cheeseman (2006).

Figure 38. Transparent Armor Bulking Phenomenon.

Obliquity is another factor that can contribute to an armor's performance. Obliquity is essentially a manipulation of an armor's dimensionality to optimize the amount of mass in the trajectory of the threat. Obliquity also imparts transverse forces, orthogonal to the armor strike face, on the projectile upon impact, redirecting the projectile trajectory toward the wider dimensions of the armor plate. The critical fact with obliquity is that its benefits rely heavily on the trajectory of the threat. Figure 39 shows how obliquity employs the angularity of an armor plate to optimize the mass on the trajectory of the threat. While employing the angularity to obtain the trajectorial mass benefit, the length of the plate must grow significantly to maintain the same height of coverage. However, in growing the length of the plate, the mass benefit is essentially lost. This can be mitigated by assuming risk related to where the oblique armor is placed. Obliquity is used in the location of highest threat impact, often at the expense of armor mass in less engaged areas. An example of this is the placement

of armor on combat vehicles. Often the frontal area is the most heavily armored, and the oblique armors on the top side of the combat vehicle are least armored.



Obliquity can increase material thickness at the projective point of impact and trajectory.

Note the sloped wall shows a 50% increase in thickness. This oblique angle would be more difficult to penetrate than a normal impact angle because of the increase in mass in the path of the projectile. Obliquity also imparts transverse loads on the threat which can cause it to pitch and yaw reducing its penetration.

Figure 39. Armor Obliquity.

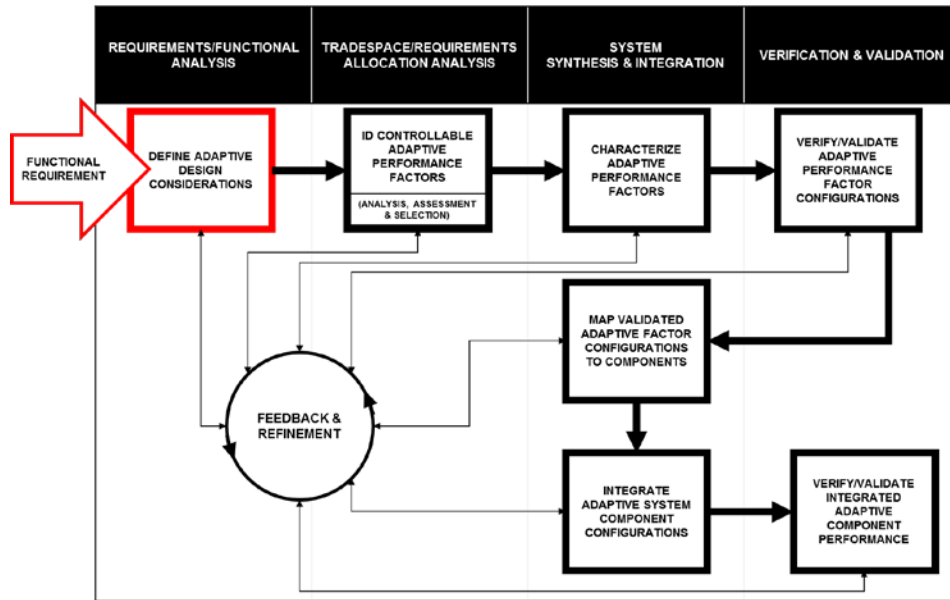
Armor technology is a mature field and a ripe candidate for the enhanced capability provided by adaptive resilience. Armor technologies to date have been largely nonadaptive. The status quo typically involves an optimized stack of metallic and composite materials that provide protection up to a prescribed scale or class of threat. Through the integration of adaptive resilience, enhanced performance, particularly in complex threat environments, can be realized.

B. CASE STUDY: ADAPTIVE RESILIENT ARMOR

In the following paragraphs, the MSIAR will be applied to a set of armor requirements for the cancelled U.S. Army ground combat vehicle (GCV) program. The GCV was an U.S. Army infantry fighting vehicle concept designed to operate across the full range of conflict types, providing unmatched state-of-the-art survivability and protection while transporting a full nine-person squad plus crew. However, in the prescribed requirements, the GCV would have weighed anywhere from 64 to 84 tons, making it as large as the M1 Abrams tank and twice as heavy as the currently fielded U.S. Army infantry fighting vehicle, the M2 Bradley IFV (Kempinski and Murphy 2012). The GCV program ended in February 2014 because of U.S. Department of Defense budget cuts, among other reasons (Defense News 2014). The GCV program was a textbook case in which competing functional requirements drove the system toward unsuitable system design. This fact makes the GCV requirements a perfect starting point for this case study. The program also serves as the most recent basis for armor protection requirements. These requirements were delivered in a draft capability development document (CDD). This CDD will be the reference for armor requirements as the methodology for the system integration of adaptive resilience is applied.

Figure 40 shows step 1 of the MSIAR. Vehicle armors that function in complex operating environments must have the ability to protect against the multitude of conventional threats as well as the ability to protect against emerging and improvised threats whose penetration characteristics are yet unknown. This need is challenging. Current and traditional armors provide protection up to a known limit. If that limit is exceeded by an emerging threat, new or additional armor must be integrated into the vehicle, which usually increases the armor system's mass and volume, thus implicating the vehicle's mobility and performance. Additionally, this new armor requires significant time to design, manufacture, and integrate into a vehicle fleet. This time element poses a problem for the vehicle systems with obsolete or overmatched armor; they are operationally vulnerable during this time.

1. Define Adaptive Design Considerations



Step 1 of the MSIAR seeks to answer the following question: “What is the desirable range of adaptive system performance (with respect to parasitic capacity and system resilience) which meets the functional requirement?”

Figure 40. Step 1: Define Adaptive Design Considerations.

a. Operational Need

To conduct this analysis and definition for adaptive design considerations, the draft GCV capability definition (CDD) document will be used as a reference. The CDD identified seven current and future capability gaps that the new GCV would prioritize in this system’s development: protection, sustainment, support networking, transportability, mobility, growth, and lethality. Three of these system descriptors and characteristics had direct or significant implication on the design of a GCV armor system and were specified as priorities and gaps for the GCV program: protection, transportability, and mobility.

Protection is described by the CDD as mobile and modular armor that provides mission flexibility for the commander while protecting the force and allowing for future technology upgrades. Transportability of the GCV system referred to the ability to transport by a range of lift and strategic mobility assets, specifically the C17 and C5 fixed-winged aircraft. Mobility was described by the CDD as a GCV that is maneuverable to ensure

tactical mobility in complex terrain and to overcome enemy counter mobility efforts. These three needs will shape and define the requirements, which will in turn shape the armor system developed for the GCV.

b. Operational Requirement

The operational need gives shape and context to the capability and functional requirements. The CDD provides specific requirements for protection, transportability, and mobility in the form of key performance parameters (KPP) and key system attributes (KSA). Figure 41. shows a comparison between the current Bradley IFV and the GCV. The applicable KPPs, KSAs and specifications are abstracted and depicted in Figure 42, Figure 43, Figure 44, and Figure 45.

	Current Bradley IFV ^a	GCV ^b
Number of Occupants		
Crew	3	3
Passengers	7 ^c	9
Physical Characteristics		
Weight (Tons) ^d	33 to 39	50 to 65
Dimensions (Feet)		
Length	23	28
Width	12.8	13.7
Height	10.6	13.7
Engine Capacity (Horsepower)	600	1,500
Armament		
Cannon (Caliber in mm)	25	25
Antitank Missile	TOW	n.a.
Machine Gun (Caliber in mm)		
RCWS	n.a.	12.7
Coaxial	7.62	7.62
Source: Congressional Budget Office based on Department of the Army, Headquarters, <i>Report on the Results of the Ground Combat Vehicle Analysis of Alternatives (Milestone A) to the Armed Services Committees of the United States Senate and House of Representatives</i> (March 2011), and other sources.		

This figure shows a comparison of characteristics for the current M2 Bradley infantry fighting vehicle (IFV) and a notional ground combat vehicle (GCV) at extrapolated design configurations based on requirements. Source: Congressional Budget Office (2013).

Figure 41. Characteristics: Current M2 Bradley IFV vs. the Projected GCV.

6.1.2 (U) System Survivability KPP 2.		
To address the potential wide range of transport (air, sea, highway, and rail) and threat concerns, the GCV IFV will require a kitting approach to attain a desired survivability level. The survivability suite will establish an integral level of survivability from a select set of threats.		
<div style="background-color: black; color: white; text-align: center; padding: 5px;">Redacted for OPSEC Purposes</div> <div style="text-align: right;">Even</div>		
after being damaged, the platform should retain the capability to protect the Soldiers inside and accomplish some portion of its primary mission until it can be evacuated and/or repaired.		
JCA	Development Threshold	Development Objective
7. Protection 7.1 Prevent	The GCV IFV will provide survivability characteristics to meet mission requirements and threat situations against the threats detailed in Table A The GCV IFV shall utilize a P3I approach to upgrade survivability capabilities over time to meet increasing threats as detailed in Table A Where armor is used it shall be modular to allow for repair and upgrade over the life of the system to meet changing threats and mission requirements.	The GCV IFV will provide survivability characteristics to meet mission requirements and threat situations against the threats detailed in Table A The GCV IFV shall utilize a P3I approach to upgrade survivability capabilities over time to meet increasing threats as detailed in Table A Where armor is used it shall be modular to allow for repair and upgrade over the life of the system to meet changing threats and mission requirements. A kitting strategy shall be used for selected threats as detailed in Table A.
	Redacted for OPSEC Purposes	Redacted for OPSEC Purposes

This figure was extracted from the draft capability definition document for the GCV. It describes the GCV system survivability key performance factor (KPP). A key performance parameter (KPP) is a descriptive metric that contains critical characteristics of an effective system. KPPs are used to build system performance specifications.
Adapted from Huggins (2013).

Figure 42. Draft GCV System Survivability Key Performance Parameter 2.

6.2.1 (U) Mobility KPP 7.		
The GCV IFV must operate within a highly fluid ABCT environment and keep pace with other vehicles within the formation. The identified KSAs are essential to the mission role of the GCV IFV within the ABCT.		
JCA	Development Threshold	Development Objective
3. Force Application 3.1 Maneuver	The GCV IFV mobility is aligned with survivability and force protection KPP requirements. The vehicle must be capable of traversing steep hills, valleys and man-made objects typical in cross-country and urban terrain. The GCV IFV must be able to maintain mobility as outlined in the HBCT OMS/MP (20 Mar 13). The mobility of the GCV IFV must be commensurate with the missions it will perform within an ABCT. Mobility is specified in the following KSAs: 30, 31, 32, 33, and 34.	Threshold = Objective

This figure was extracted from the draft capability definition document for the GCV. It describes the GCV system mobility KPP. Source: Huggins (2013).

Figure 43. Draft GCV Mobility Key Performance Parameter 7.

6.2.10 (U) Transportability KSA 7.		
GCV IFV transportability provides options for strategic deployment and options for operational maneuver in order to execute a range of missions within a campaign. This capability provides flexibility for entry operations (permissive and non-permissive) to counter threat anti-access strategies by using multiple austere entry points to bring in full combat configured units.		
JCA	Development Threshold	Development Objective
4. Logistics 4.1 Deployment & Distribution	The GCV IFV must be transportable worldwide by air, sea, highway, and rail in accordance with MIL STD 1366E and MIL STD 209K to support theater strategic deployment and theater operational maneuver using organic material handling assets. The GCV IFV will be transportable on all conveyances currently used to deploy an ABCT to ensure deployment in	The GCV IFV will be transportable by all modes of transportation, including operational maneuver by joint heavy lift.

This figure was extracted from the draft capability definition document for the GCV. It describes the GCV system transportability key system attribute (KSA). KSAs are descriptive metrics that contain attributes essential to an effective system. KSAs are also used to build system performance specifications. Source: Huggins (2013).

Figure 44. Draft GCV Transportability Key System Attribute 7.

6.2.39 Dash Speed KSA 36.		
The GCV IFV is required to operate in complex and urban terrain and must be able to quickly move in both directions to avoid target acquisition. This facilitates the ability to dash to safety, particularly in urban areas. In addition to increased mobility, this capability is essential to survivability for medium armor protected vehicles. This acceleration provides the minimum dash-to-cover capability. Also provides the ability to immediately seek cover from direct and indirect fire.		
JCA	Development Threshold	Development Objective
3. Force Application	The GCV IFV, at FCC, with engine idling must be capable of accelerating from a standing start to 48 kph (30 mph) on level hard surface road, within 22 seconds.	The GCV IFV, at FCC, with engine idling must be capable of accelerating from a standing start to 48 kph (30 mph) on level hard surface road, within 16 seconds.

This figure was extracted from the draft capability definition document for the GCV. It describes the GCV system mobility KSA. Source: Huggins (2013).

Figure 45. Draft Dash Speed Key System Attribute 36.

In summary, the applicable requirements derived from the GCV KPPs and KSAs appear in Figure 46. After analyzing these requirements, systems designers can understand the considerations they should include when integrating adaptive resilience into armor systems. These requirements will be refined into performance specifications that will further constrain the GCV system and its hosted subsystems.

- 1. The GCV must provide survivability in a kitted and modular fashion from a select set of threats.**
- 2. The GCV must be able to operate within an Armor Brigade Combat Team (ABCT) environment, keep pace with other combat vehicles in an ABCT; Specifically the GCV must be able to climb, descent, traverse side slopes, cross country and hard surfaces at prescribed average speeds of no less than 30 kph and 60 kph respectively.**
- 3. The GCV must have the strategic mobility IAW Military Standard 1366E and 209K to which the most limiting constraints are for the vehicle to be airlifted on a C17 and C5 Aircraft.**

Source: Huggins (2013).

Figure 46. GCV Requirements Selected for Adaptive Resilience Integration

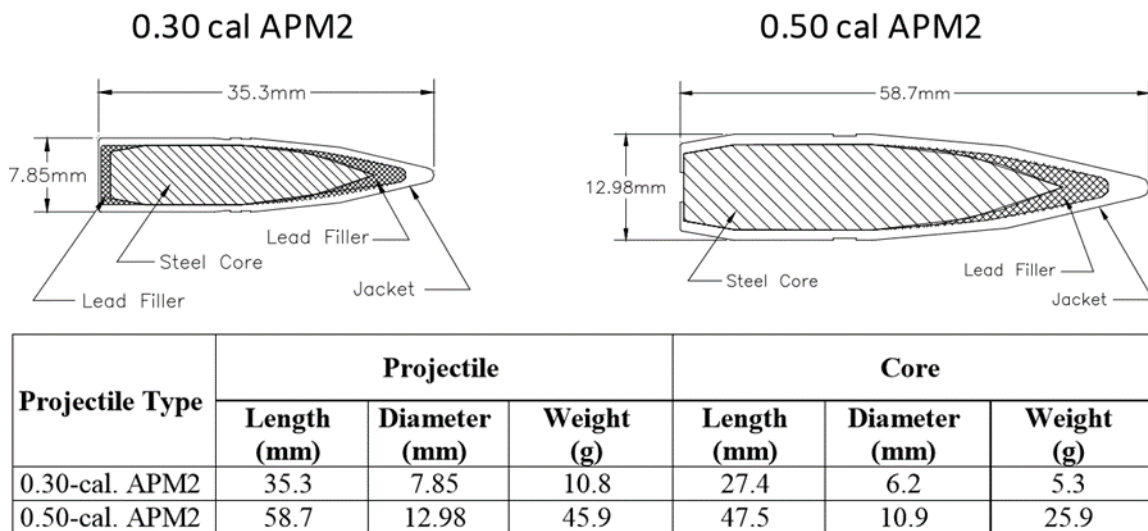
c. Survivability Adaptive Armor Constraints and Considerations

The GCV survivability requirements will be the most constraining of the adaptive armor design. The requirements in Figure 47 show that the GCV must provide protection to a broad list of threats. This threat list is classified. In an effort to keep this dissertation at the unclassified classification level, the .30-cal APM2 will be designated as the notional threshold threat, and the .50-cal APM2 will be designated as the notional objective threat (see Figure 48).

ASPEC -1825 3.1.2.2.4 Penetration Avoidance	
ASPEC -1828	The GCV IFV armor protection (excluding core structure and underbody armor) shall be modular, with the ability to, install, remove, and replace, threshold (T) and objective (O) armor modules.
ASPEC -1834	The GCV IFV shall protect all occupants in normal fighting position, primary weapon components within the turret, and mission critical mobility components within the chassis against direct-fire kinetic energy threat xx degree azimuthal, xx degree elevation at a range of xx meters, (T) and against direct-fire kinetic energy threat xx azimuthal, xx degree elevation, at a range of xx meters (O). Classified (C-PSPEC251).

This figure was extracted from the draft performance specification for the GCV. It serves as the detailed requirement for the GCV system regarding how the system avoids penetration. This function is typically performed by armor. Source: PEO Ground Combat Systems (2013).

Figure 47. Draft Performance Specification for Penetration Avoidance.



Source: Gallardy (2015).

Figure 48. Dimensional and Mass Characteristics for .30-Cal APM2 and .50-Cal APM2.

Additionally, this dissertation will assume the simplest azimuthal trajectory, elevational trajectory, and range—0°, 0°, and muzzle distance, respectively. The survivability

requirements state that the armor system shall be modular, with the ability to install, remove, and replace at threshold and objective levels (.30-cal and .50-cal). This requirement implies that the armor must incorporate Adaptive Mode 2, external reconfigurations. The resultant adaptive design consideration can be stated as follows:

The adaptive armor design must be able to prevent the penetrations of .30-cal APM2 threats at the threshold and .50-cal APM2 threats at objective levels through Adaptive Mode 1 (internal reconfiguration) and Adaptive Mode 2 (external reconfiguration) at 50% reduction of weight from a fixed RHA armor system.

d. Mobility Adaptive Armor Considerations

The mobility requirements shown in Figure 49 will shape the weight of the adaptive armor design. The mobility requirement essentially states that the GCV must be able to accelerate to a speed of 30 mph within a threshold time of 22 seconds and an objective time of 16 seconds. This requirement will largely be achieved by the power the engine transmits to the powertrain. This power derives from the amount of force the engine can generate multiplied by the speed at which it can transmit it. Force is only one component of acceleration. The other component is mass. Acceleration derives from force divided by mass. Therefore, the greater the mass of a body, the more force will be required to accelerate it. As previously stated, this requirement is largely met with the power plant and the drivetrain of the GCV; however, minimizing the weight of the armor system can pay significant dividends in meeting this requirement. Therefore, the resultant adaptive armor design consideration can be stated as follows:

The adaptive armor design must achieve the maximum amount of ballistic performance from the least amount of weight.

ASPEC -1618 3.1.2.1.1.1 Dash Speed	
ASPEC -1619	The GCV IFV, at FCC, with engine idling, on a level hard surface road, shall accelerate from a standing start to 48 kph (30 mph) within 22 seconds (T), and within 16 seconds (O).

This figure was extracted from the draft performance specification for the GCV. It serves as the detailed requirement for the GCV system regarding how the system can rapidly accelerate. Acceleration is a function of force divided by mass. The less mass a system has, the less force is required to accelerate it. The leading subsystem that contributes to a ground platform's mass is its armor structure. The lighter a ground platform's armor, the more efficient and quicker it will be able to accelerate. Source: PEO Ground Combat Systems (2013).

Figure 49. Draft Performance Specification for Dash Speed.

e. Transportability Adaptive Armor Considerations

The transportability requirements listed in Figure 50. shape both the weight and dimensions of the GCV. The military standard that governs the transportability constraints is MILSTD 1366E. This standard dictates many modes of strategic mobility and transportability, such as rail, ship, truck, and air.

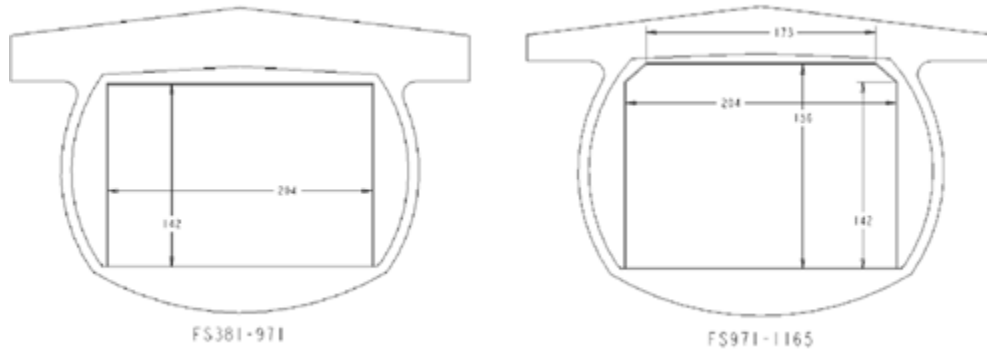
ASPEC -2775 3.1.7.7.1 Air	
ASPEC -2776	The GCV IFV shall, in its Transport Configuration - if applicable, be transportable on C-17 & C-5 aircraft in compliance with MILSTD 1366E. (T=O

This figure was extracted from the draft performance specification for the GCV. It serves as the detailed requirement for the GCV system regarding how the system can be strategically transported. The air platforms listed are constrained in their volumetric and mass payloads. The GCV armor system's dimensionality and weight must meet those dimensional and mass constraints of the platform to meet this performance specification. Source: PEO Ground Combat Systems (2013).

Figure 50. Draft Performance Specification for Air Transportability.

For this analysis, the most restrictive standard will be used: the C17 aircraft constraints shown on the left side of Figure 51. Air transport is the fastest mode, giving nations with this capability a strategic advantage in terms of responding quickly to a contingency operation. However, dimensions and weight on aircraft come at a premium cost. In width, the C17 is the most restrictive at 204 inches, or 17 feet. The current M2 Bradley

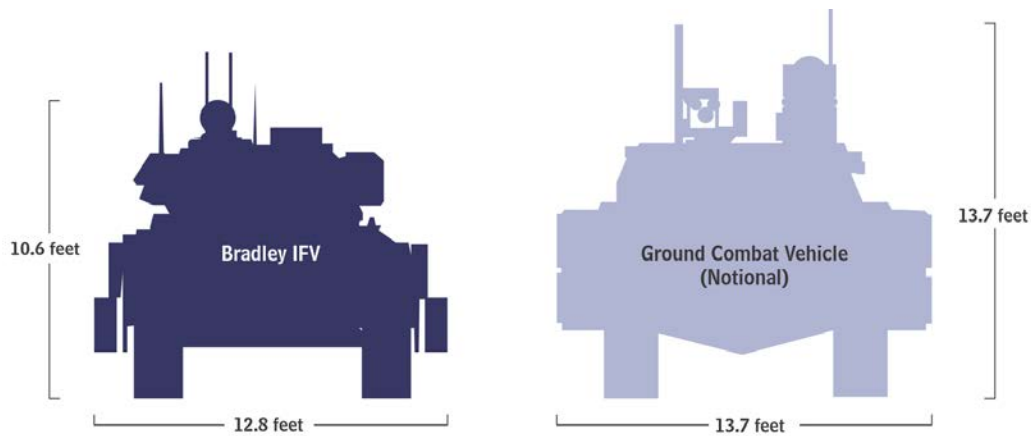
IFV width at full combat configuration is 12.8 feet. The notionally designed GCV was templated to be 13.7 feet wide.



This figure depicts the internal width and height constraints in the cargo holds of a C17 and a C17 ER. These measurements are in inches. The GCV strategic transportability specification requires the system to be air-transportable by C17 and C5. The C17 is the most restrictive dimensionally of the two aircraft. Source: MIL-STD-1366E (2006).

Figure 51. C17/C17 ER Equipment Design Limit Cross Section.

Comparing the C17 dimensions to the notional GCV dimensions shown in Figure 51, only 18 to 24 inches of space remain on either side of the notional GCV design if it were to be loaded on to a C17 aircraft. This is acceptable but still dramatically wide. The width of a vehicle also has significant implications in terms of its tactical mobility. In restrictive urban, forested, or mountainous environments, wide vehicles are restricted to wide corridors. It is in the military's best interest to keep this vehicle as narrow as possible but not to exceed 13.7 feet. On top of the GCV aircraft dimension constraints, weight also plays a major role.



This figure depicts the dimensions of a fully equipped M2 Bradley AFV and the notional Ground Combat Vehicle. The notional GCV was predicted to be 11 inches wider than the Bradley. Source: Congressional Budget Office (2013).

Figure 52. Dimensions: Current M2 Bradley IFV vs. Notional GCV.

Table 3 shows the cargo deck weigh capacities for the C5 and C17. The C5 can lift 90 tons, and the C17 can lift approximately 65 tons on its cargo deck.

Table 3. C17/C17ER/C5 Cross-Section and Lift Limits

Aircraft	Equipment Design Dimensions (inches, m) ¹			Aircraft Capabilities ²	
	Length	Width	Height	ACL for 3,200 nm (lb, kg)	Range (nm) w/max ACL (lb, kg) ³
C-17/C-17ER cargo deck	784 19.9	204 5.2 ⁴	142 to 156 3.6 to 4.0 ⁵	130,000 58 900	2,300 nm 167,400/164,900 75,931/76,158
C-17/C-17ER ramp	238 6.0	204 5.2	127 3.2	40,000 ⁶ 18 144	40,000 ⁶ 18 144
C-5 cargo deck	1,454 36.9	216 5.4	156 3.9	178,000 80 700	1,600/265,000 1,600/120,200
C-5 fwd ramp	116 2.9	216 5.4	142 3.6	15,000 ⁶ 6804	15,000 ⁶ 6804
C-5 aft ramp	155 3.9	216 5.4	142 3.6	15,000 ⁶ 6804	15,000 ⁶ 6804

1. Dimensions allow for 6-inch (152 mm) clearance top and both sides. Length dimension does not include usable ramp area (fore and aft on C-5). Compliance with these dimensions does not guarantee an item will be certified for transport in an AMC aircraft. See MIL-HDBK-1791 for details.
2. Refer to AF Pamphlet (AFP) 10-1403 and MIL-HDBK-1791 for detailed aircraft limits.
3. Published Allowable Cabin Load (ACL). Range based on still air, one-way, and flying at best altitude/cruise speed. It is very rare for the aircraft to fly with these ACLs. These ACLs are included for information only and should not be used for design purposes.
4. Front section of cargo deck is only 116 inches (2.9 m) wide. This portion has been excluded from the 784 inch length.
5. The height of the cargo deck is 142 inches under and forward of the wing box and 156 inches aft of the wing box.
6. Maximum load allowed on ramp, independent of range. Ramp payload is part of maximum aircraft payload.

Source: MIL-STD-1366E (2006).

When it comes to strategic mobility, less weight is best. The current C17 and C5 can easily lift two M2 Bradley IFVs. These platform dimension and weight constraints limit GCV strategic mobility to one system per aircraft, as opposed to the current ability to carry two M2 Bradleys. Nonetheless the system still maintains the ability to be strategically transported by air. Therefore, the adaptive design consideration defined for mobility also has application in transportability. The resultant adaptive armor design consideration for transportability can be stated as follows:

The integrated adaptive resilient armor design when integrated on the host GCV platform may not exceed 204 inches of total GCV system width during strategic transport.

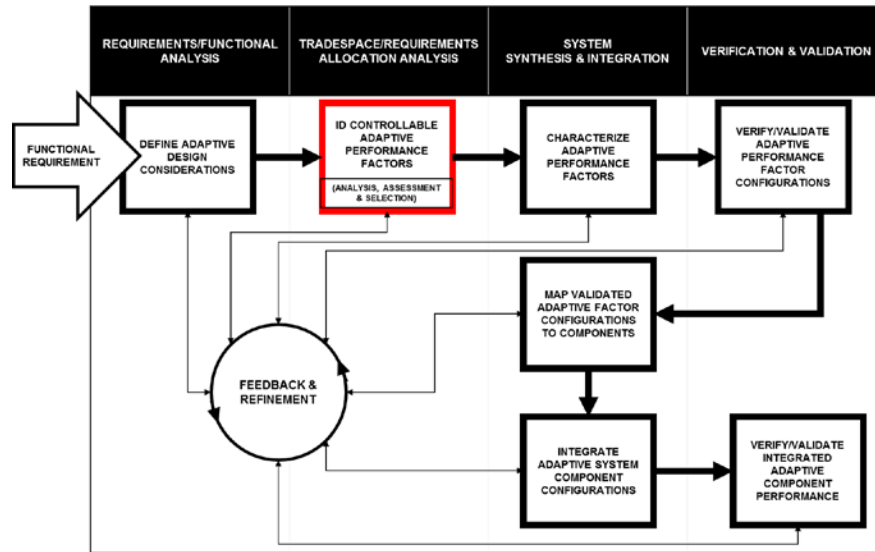
f. Adaptive Armor Design Consideration Summary

In summary, the GCV's armors must minimize weight and volume yet counter the notional threshold .30-cal APM2 and objective .50-cal APM2 threats. In addition, if an armor is overmatched by an unaccounted for threat, the architecture of the armor/vehicle system must be able to scale or adapt in a rapid and modular fashion. A GCV armor system that can do these things effectively will have achieved a state of adaptive resilience, as summarized in Table 4.

Table 4. Adaptive Armor Design Considerations

Adaptive Armor Design Considerations:	
ADC 1:	The adaptive armor design must be able to prevent the penetrations of .30 cal APM2 threats at the threshold and .50 cal APM2 threats at objective levels through adaptive mode one (internal reconfiguration) and adaptive mode two (external reconfiguration) at 50% reduction of weight from a Fixed RHA Armor System.
ADC 2:	The adaptive armor design must achieve the maximum amount of ballistic protection from the least amount of weight.
ADC 3:	The integrated adaptive resilient armor design while integrated on the host GCV platform may not exceed 204 inches of total GCV system width during strategic transport.

2. Identify Controllable/Adaptive Performance Factors



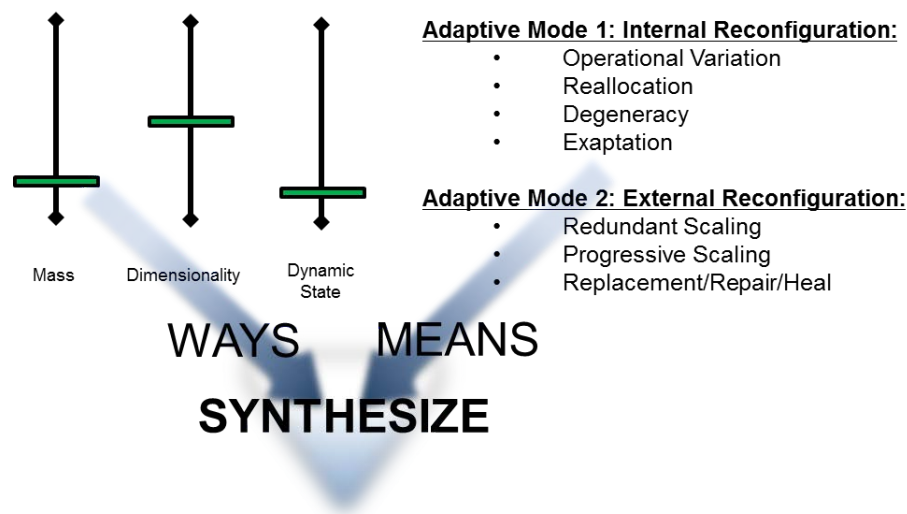
Step 2 of the MSIAR seeks to answer two questions. What are the best controllable adaptive performance factors or parameters that can be effectively manipulated to scale, modify or otherwise adapt the function. What are the suitable modes of adaptability to employ in realizing those controllable adaptive performance factors?

Figure 53. Step 2: Identify Controllable/Adaptive Performance Factors

Figure 53. depicts step 2 of the MSIAR. With the adaptive design considerations defined, the controllable or adaptive performance factors must now be identified to determine which armor system parameters can be manipulated to achieve the requirements and adaptive design considerations. Functional parameters or factors are independent attributes of a function that dictate the performance or output of that function. In other words, this step of the methodology identifies the controllable independent performance variable(s) on which the adaptive function depends. Controllability is critical, because if the factor cannot be actively manipulated, then the user cannot adapt it for the desired performance. Armor systems derive their fundamental functionality from the transfer of momentum from threat to the armor system. This is observed in the Newtonian penetration equation (Equation 5) presented at the beginning of the armor primer. The physics of armor and threat interaction are governed by the law of conservation of energy. The key factors driving threat and armor performance are the armor material properties, armor mass, armor dimensionality, and physics of the threat and armor interaction (kinetic energy and momentum). Thinking adaptively, threats, whether conventional or improvised, employ a range of masses

accelerated to a range of velocities to achieve a range of kinetic energies to penetrate an armor. An armor designer who can effectively manipulate these factors in a meaningful and timely fashion can create an adaptive armor technology to prevent a threat's penetration.

Traditional armor designs use a material with a fixed material mass bolted onto a vehicle in some dimensional configuration that statically absorbs the kinetic energy or momentum (velocity, dimensionality, and mass) of the incoming threat upon its impact. So an adaptive resilient armor would need to have the ability to somehow manipulate its mass, dimensionality, and velocity over a range of values in a fashion to counter the penetrating threat's kinetic energy effectively. Although material properties are controllable, they would only be useful in Adaptive Mode 2, requiring an external reconfiguration. Therefore, mass and dimensionality are the most controllable system performance factors needed for an adaptive armor. With the factors identified, an armor designer could synthesize them with means to achieve the adaptive ends. The means are the adaptive modes discussed in Chapter II. Next, the armor designer must identify ways to manipulate the factors using the means described in the two adaptive modes (see Figure 54).



Adaptive performance factors can be considered the “ways” in which adaptive resilience can be achieved while the adaptive modes can be considered the “means” to achieve adaptive resilience.

Figure 54. Adaptive Mode and Adaptive Design Consideration Synthesis.

a. Adaptive Mass

How can an armor designer manipulate the mass of an armor? There are several ways. Obliquity is the first method. If obliquity could be optimized at the point of threat impact in real time, ballistic performance of the armor could be adaptively improved through the increase in mass on the trajectory of the threat. Armor obliquity can be readily manipulated on vehicles with the right mechanisms. As shown in Figure 55, a simple shift of 30° can result in an increase of approximately 25% ballistic mass efficiency. This example employs two factors mass and dimensionality adapted through operational variation. Reallocation is another method. Typically armors are engaged from one direction. This leaves the armor on the opposite side of the engagement unutilized. By reallocating this armor to the engaged side of the vehicle, more protection can be achieved. This could be useful in a situation where terrain eliminates the possibility of attack from a certain direction, or as a resilient mode of recovery if a noncatastrophic penetration occurred and the vehicle needs more protection on that side. This is much more difficult but possible with the right technologies.

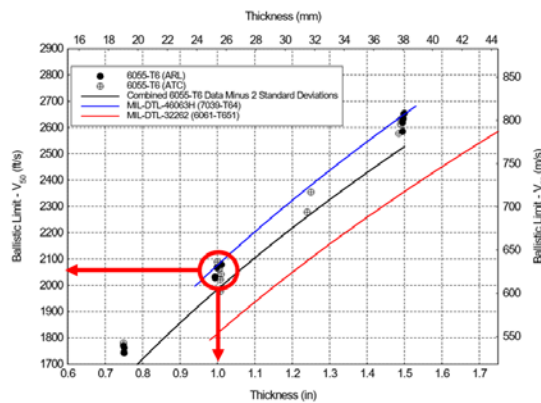


Fig. 5 Ballistic limit vs. thickness of AA6055 as compared to existing specs for the .30-cal APM2 at 0° obliquity

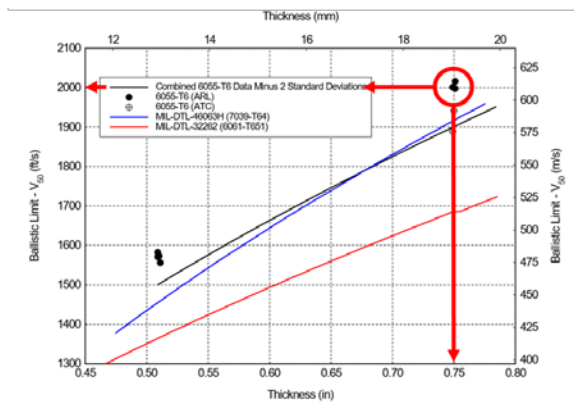


Fig. 4 Ballistic limit vs. thickness of AA6055 as compared to existing specs for the .30-cal APM2 at 30° obliquity

The heavy red lines on each graph show that at approximately the same impact velocity (2000 fps), a .30 cal APM2 stops in a 1- inch plate at 0° obliquity, while stopping in a .75-inch plate at 30° obliquity. Adapted from Gallardy (2015).

Figure 55. V_{50} Ballistic Limit Differences in Aluminum Armor for .30 cal APM2.

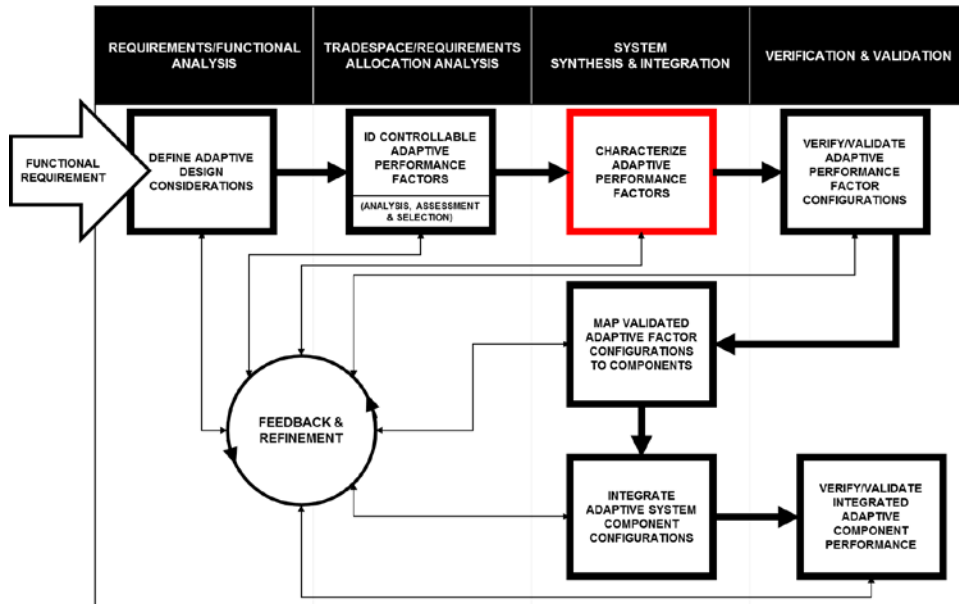
b. Adaptive Dimensionality

Besides obliquity, adaptive dimensionality can be achieved using adaptive spaces in the armor. Two half-inch plates of steel with a space between them will have greater ballistic performance than will a single 1-inch plate of steel. Two half-inch plates at two inches apart will have greater ballistic performance than two half-inch plates with only one inch of separation (Hurlich 1950). Manipulating the space between plates would be relatively simple with the right mechanisms.

c. Adaptive Dynamic State

Adaptive dynamic state can be simply achieved using any controllable kinetic energy stimulation mechanism attached to the armor. However, this is most likely unnecessary overkill given the two threats of interest for this case study. These threats are easily defeated with passive or static armors. A passive way to manipulate the dynamic response of an armor during a threat engagement would be through momentum transfer. As previously stated, most armors are static plates of material bolted to the side of a vehicle. If the armor were able to dynamically travel and interface with the threat longer, it could steal more kinetic energy and disrupt its trajectory. An armor that would partially give way with the threat or ride along with it during its plastic deformation could have valuable ballistic implications. Through external reconfiguration, the mass and thus momentum response of the armor could be optimally tuned to any threat of interest.

3. Characterize Adaptive Performance Factor Configurations



Step 3 of the MSIAR seeks to answer the following question: Which range of selected controllable factor configurations achieve the Adaptive Design Considerations?

Figure 56. Step 3: Characterize Adaptive Performance Factors.

Figure 56. depicts step 3 of the MSIAR. Performance factor solution configurations are the factor states that meet or move the system performance toward the desired function performance specified in the requirements. In other words, referring back to the algebraic function discussed in Chapter III, the performance factor solution configuration for that function is the specific independent variable value(s) that achieve the desired dependent variable values or range of values. This same thought process must now be applied to the armor system. The innate system performance factors (inputs) that were previously identified for the armor could serve as a measure of dimensionality, dynamic velocity of an armor plate, or the density of a candidate armor material. By analyzing the armor's ballistic performance (output) based on statistically relevant samples of data at these factor inputs, a linear or nonlinear function could be generated that functionally characterizes the effects of the dimensionality, plate dynamics, or density toward the ballistic performance of the total system. Varying these factors or combinations of factors creates adaptive system configurations or functional states with a range of outputs. Knowing how the variability in the independent factor configurations implicate the dependent performance output enables

system design engineers to understand and confidently predict how changes to the factors (dimensionality, dynamics, or density) affect performance output (ballistic resistance). By integrating these variable ranges of performance or adaptive capacity into the system, engineers could create an armor system in which the ballistic performance could be confidently adapted in real time to protect against adaptive threat application.

Conceptually describing this step seems simple enough; however, it can be challenging to find the needed data to be able to characterize the controllable factors. If the data are readily available, simple engineering analysis and manipulation of the data can serve the need. However, if the data do not exist, they must be created. This can be accomplished through numerous methods, including modeling, simulation, and physical experimentation. The following paragraphs outline the use of available data and show how experimentation can be used to achieve these ends.

a. Mass Characterization through Data Analysis

As discussed during the armor primer, mass or density of armor is typically described in a measure called areal density. To characterize the needed mass or areal density needed to meet the threat-defeat threshold and objective requirements, ballistic threat data are required. The most common armor and standard comparative armor material is known as MIL-DTL-12560 rolled homogenous armor (RHA). A large amount of ballistic data are available for this armor material. This data can be seen in Tables 5 and 6. In addition, because this armor material has a military specification associated with it, this reference will be used to collect the needed ballistic reference data. The needed data can be seen in Tables 5 and 6. These tables were pulled from MIL-DTL-12560. This specification states that the V_{50} ballistic limit for RHA at muzzle velocity (2700 fps) for the threshold .30-cal APM2 is .60". The specification specifies that the V_{50} ballistic limit for RHA at muzzle velocity (2700 fps) for the objective .50-cal APM2 is 1.015". RHA at 1 inch thickness has an areal density of approximately 40 psf. Therefore, the threshold and objective V_{50} ballistic limits areal densities are 25 psf and 41 psf, respectively. Recall that the V_{50} is the ballistic limit for the projectile velocity at which 50 of 100 shots will completely penetrate the plate. A 50% probability of defeat does not equal protection. Therefore, the actual required areal density

for protection is much heavier. To avoid any classification documentation issues, doubling the V_{50} thickness will serve as a conservative approximation of required RHA thickness for complete ballistic protection from these threats. Thus, an armor must have perform in an equivalent manner as a 48 psf RHA armor to protect against the notional GCV threshold threat .30-cal APM2. To meet the .50-cal APM2 objective protection level, an armor must have equivalent protective performance to an RHA armor at an areal density of 80 psf. To meet the adaptive design considerations, the armor must protect against the threshold and objective threats at 50% of those values. This would require an adaptive armor capable of protecting against the threshold threat at 24 psf and the objective threat 40 psf.

With this information, characterization of the required armor mass or areal density is complete. Conveniently, the threshold and objective value create a range of armor masses. This range will serve as the mass range of adaptation or adaptive capacity for an adaptive resilient armor. The doubled V_{50} will be considered the threshold armor areal density because it is heavier and less desirable from a system perspective. The single V_{50} will serve as the objective adaptive armor areal density because it is lighter and thus more challenging to achieve protection consistently at the lighter weight.

Table 5. Minimum Required V₅₀ Ballistic Limits for .30-cal APM2 at 0°

TABLE A-III. <u>Minimum required ballistic limits (protection criteria) for Class 1 & 4 armor, firing obliquity: 0°, projectile: caliber .30 M2 AP.</u>					
Thickness, inches	Required BL(P), ft/sec CLASS 1 & 4	Thickness, inches	Required BL(P), ft/sec CLASS 1 & 4	Thickness, inches	Required BL(P), ft/sec CLASS 1 & 4
0.230	1509	0.370	2045	0.515	2484
0.235	1532	0.375	2062	0.520	2498
0.240	1554	0.380	2078	0.525	2512
0.245	1575	0.385	2095	0.530	2525
0.250	1596	0.390	2111	0.535	2539
0.251 ^{1/}	1600	0.395	2127	0.540	2552
0.255	1618	0.400	2143	0.545	2566
0.260	1638	0.405	2159	0.550	2579
0.265	1659	0.410	2175	0.555	2593
0.270	1679	0.415	2191	0.560	2606
0.275	1699	0.420	2206	0.565	2619
0.280	1719	0.425	2222	0.570	2632
0.285	1739	0.430	2237	0.575	2645
0.290	1758	0.435	2252	0.580	2658
0.295	1778	0.440	2267	0.585	2671
0.300	1797	0.445	2282	0.590	2684
0.305	1815	0.450	2297	0.595	2697
0.310	1834	0.455	2312	0.600	2710
0.315	1853	0.460	2327	0.605	2723
0.320	1871	0.465	2342	0.610	2736
0.325	1889	0.470	2356	0.615	2749
0.330	1907	0.475	2371	0.620	2762
0.335	1925	0.480	2385	0.624 ^{2/}	2772
0.340	1942	0.485	2400	0.625	2775
0.345	1960	0.490	2414	0.630	2788
0.350	1977	0.495	2428	0.635	2801
0.355	1994	0.500	2442	0.640	2814
0.360	2011	0.505	2456	0.645	2827
0.365	2028	0.510	2470	0.650	2840

The value bordered in red is the plate thickness determined to achieve a 50% probability of completely stopping the threat. This means that out of 100 threshold threat projectiles fired at the muzzle velocity of 2700 fps a plate of .600" thick, 50 projectiles will pass through, and 50 will be stopped. This value does not assure ballistic protection at this thickness, but rather states the very threshold of the required plate thickness for ballistic protection at this threat velocity. Adapted from MIL-DTL-12560J (MR) (2009).

Table 6. Minimum Required V_{50} Ballistic Limits for .50-cal APM2 at 0°

TABLE A-V. Minimum required ballistic limits (protection criteria) for Class 1, 3 & 4 armor and the upper ballistic limits for Class 3 armor; firing obliquity: 0°, projectile: caliber .50 M2 AP-Continued.

Thickness, inches	BL(P), ft/sec		Thickness, inches	BL(P), ft/sec		Thickness, inches	BL(P), ft/sec	
	CLASS			CLASS			CLASS	
	1, 3 & 4 Min	3 Max		1, 3 & 4 Min	3 Max		1, 3 & 4 Min	3 Max
0.995	2673	2819	1.065	2775	2921	1.135	2874	3020
1.000	2680	2826	1.070	2782	2928	1.140	2881	3027
1.005	2688	2834	1.075	2790	2936	1.145	2888	3034
1.010	2695	2841	1.080	2797	2943	1.150	2895	3041
1.015	2702	2848	1.085	2804	2950	1.155	2902	3048
1.020	2710	2856	1.090	2811	2957	1.160	2909	3055
1.025	2717	2863	1.095	2818	2964	1.165	2915	3061
1.030	2724	2870	1.100	2825	2971	1.170	2922	3068
1.035	2732	2878	1.105	2832	2978	1.175	2929	3075
1.040	2739	2885	1.110	2839	2985	1.180	2936	3082
1.045	2746	2892	1.115	2846	2992	1.185	2943	3089
1.050	2754	2900	1.120	2853	2999	1.190	2949	3095
1.055	2761	2907	1.125 ^{2/}	2860	3006	1.195	2956	3102
1.060	2768	2914	1.130	2867	3013	1.200	2963	3109

The value bordered in red is the plate thickness determined to achieve a 50% probability of completely stopping the threat. This means that out of 100 objective threat projectiles fired at the muzzle velocity of 2700 fps a plate of 1.015" thick, 50 projectiles will pass through, and 50 will be stopped. This value does not assure ballistic protection at this thickness, but rather states the very threshold of the required plate thickness for ballistic protection at this threat velocity. Adapted from MIL-DTL-12560J (MR) (2009).

b. Characterization of Dynamic State through Analysis

Characterization of dynamic state is difficult without capable tools and computing resources. However, a simple characterization analysis can be conducted using the law of energy conservation. Essentially, the law of energy conservation states that there can be no energy loss during an interaction of differing bodies of mass. This interaction assumes the collision is occurring in a perfectly closed system. For this example, assume this collision is occurring in a perfectly closed system. The two bodies of mass in a ballistic event are the armor and the threat projectile. Because a ballistic event occurs in milliseconds, the effects of the potential energy change are minor and can be ignored. An armor is meant to terminate a ballistic event, or in other words, terminate the KE of the threat. Therefore, the resultant conservation of energy equation appears in Equation 6, as follows:

$$\Sigma KE_1 - \Sigma KE_2 = 0$$

or

$$\left(\left(\frac{1}{2}mv^2 \right)_{projectile_1} + \left(\frac{1}{2}mv^2 \right)_{armor_1} \right) - \left(\left(\frac{1}{2}mv^2 \right)_{projectile_2} + \left(\frac{1}{2}mv^2 \right)_{armor_2} \right) = 0$$

where :

KE_1 = Kinetic Energy Before Collision

(6)

KE_2 = Kinetic Energy After Collision

m = Mass

v = Velocity

$projectile_1$ = Projectile Before Impact

$armor_1$ = Armor Before Impact

$projectile_2$ = Projectile During Impact

$armor_{21}$ = Armor During Impact

The threshold and objective threats have a mass of 10.8 grams and 45.9 grams, respectively. This mass can be converted to grains, which is a common mass measure used in ballistics. Thus, the threshold and objective threats measures are 166 and 400 grains, respectively. This mass, combined with the muzzle velocity (2700 fps) in the KE equation (Equation 6), results in 2697 ft-lbs and 6469 ft-lbs of kinetic energy. This is the incoming energy associated with the two threats of interest. This means that the armor system must absorb, redirect, or otherwise mitigate this energy to stop the penetrating threat. Armor typically does this through fixed plates that plastically deform upon impact to absorb the energy. The collision event is what terminates the kinetic energy in the system.

In the previous adaptive factor characterization paragraphs, it was shown that an RHA plate is capable of terminating the kinetic energy in a fixed dynamic state at the V_{50} areal densities of 24 and 40 psf, respectively, for the threshold and objective threat. If that plate has a dynamic state other than zero (fixed), it will have an effect on balancing the conservation of energy shown in Equation 6. If the plate is moving toward the projectile, that will have a cancelling effect on kinetic energy of the particle. However, if the plate is moving too fast in the opposite direction (hypervelocity), the plate material will begin behaving like a fluid upon impact, and its material properties will have a degraded terminal effect. This is according to a lecture presentation given by Marc Adams of the California Institute of Technology on the phenomena associated with hyper velocity impacts. If the plate is moving

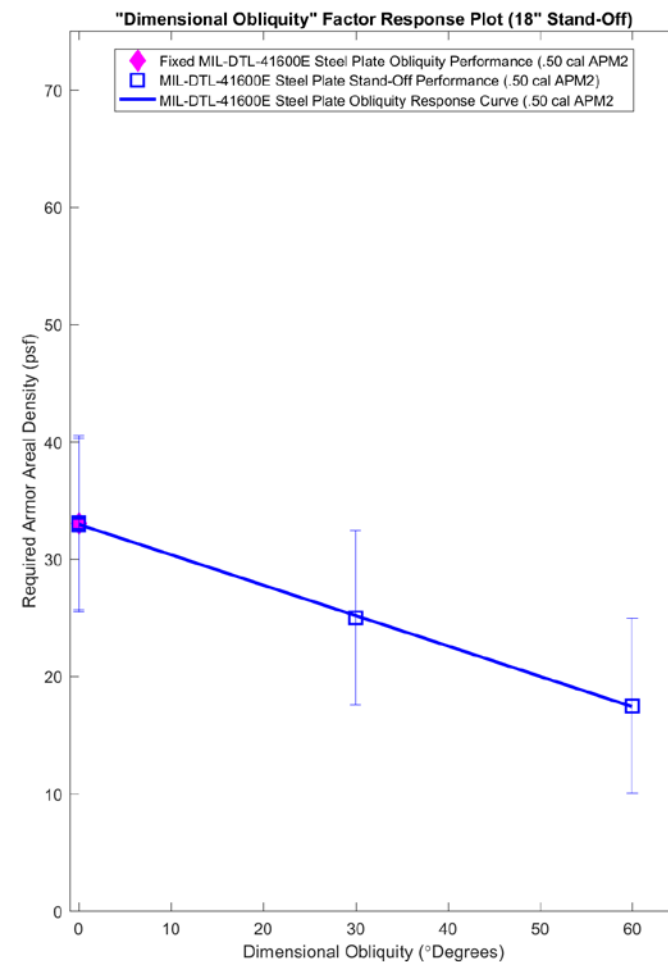
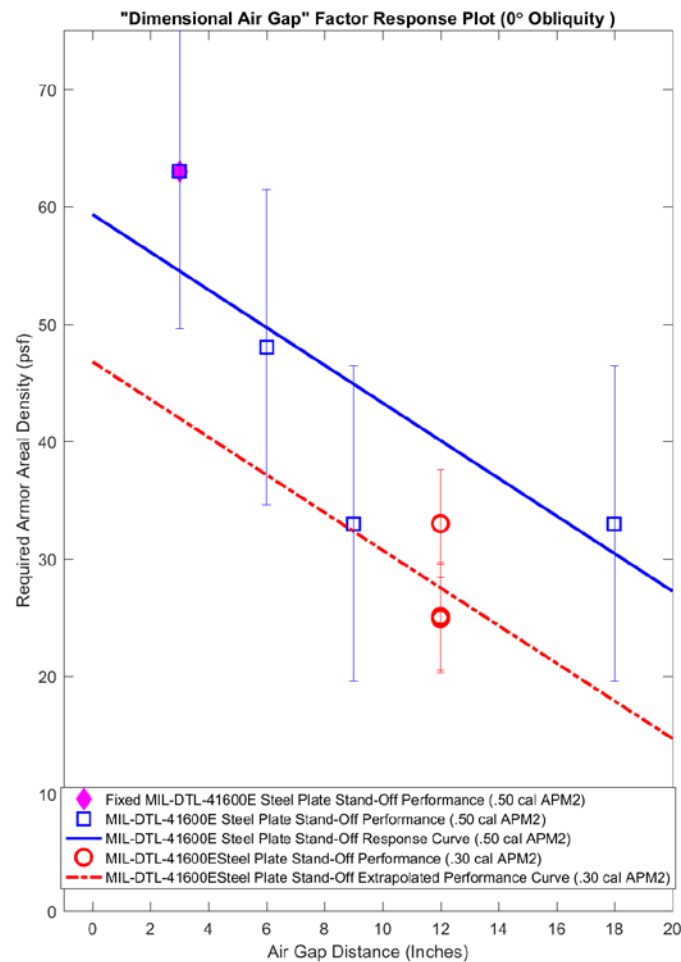
in the same direction, it could add to or subtract from the penetration performance of the projectile. Without significant mechanics of material analysis and finite element physics analysis, characterizing the dynamic state as an adaptive factor is difficult. However, it can be confidently stated that dynamic state does affect ballistic performance, and further, that if an armor system employs dynamic state as a performance factor, then that specific design should be characterized. Generalizations on this adaptive factor cannot be readily made without knowing the specific way it will be employed. This means that if this factor is to be used in the creation of an adaptive resilient armor system, the material makeup and mass of the system must be known. This will not happen until physical components are mapped to the adaptive factors configurations in step 5 of the MSIAR. Therefore, this adaptive factor cannot be characterized until after step 5.

c. Dimensionality Characterization through Experimentation

In the event that the characterization of a controllable performance factor cannot be achieved through existing data analysis, experimentation may be required to generate the data needed for the characterization. This may be especially true because very few systems employ adaptive means for performance factors. This means that establishing a range of characterization values could be difficult using existing data. This was the case for analyzing armor dimensionality. Data were available for monolithic plates at 0° and 30° obliquity but not for any other obliquities. This lack of data also held true for spaced armors. Very specific spaced armor data were available but none that fit the weight constraints required for this analysis. Therefore, experimentation was conducted with respect to an adaptive standoff and obliquity with respect to mass.

In this experiment, a plate of quarter-inch MIL-DTL-41600E steel (high hard) was placed in front of a semi-infinite stack of MIL-DTL-32262 aluminum plate (6061-T651 Type 200). This material was chosen as a baseline for the experiment because quarter-inch high hard steel combined with softer aluminum represents a high-performing, common composite spaced ballistic armor. This is similar to a high hard applique armor on an aluminum hull commonly seen on combat vehicles. In this structure, the quarter-inch of high hard steel served as the adaptive plate, and the aluminum served as a fixed ballistic witness or catcher of spall and debris from the threat and high hard plate. In other words, the strike face

obliquity and the stand-off/air gap manipulation for the adaptive armor was achieved through the high hard plate. Figure 57. shows the ballistic experiment results.



These graphs depict the residual plate penetration of the threshold and objective threats into MIL-DTL-32262 aluminum plate after striking various obliquities and air gaps of a .25-inch plate MIL-DTL-41600E steel. Data on such an armor target at adaptive obliquity and air gaps design points do not exist. Therefore, characterization experiments were required to acquire such data.

Figure 57. Ballistic Experiments with MIL-DTL-41600E Steel and MIL-DTL-32262 Aluminum Plate vs. .50-cal APM2

Experiments were conducted primarily with .50-cal APM2 because of resource constraints. Three shots were conducted with .30 cal APM2. The .50-cal APM2 was selected for its more stressing performance against the armor. The three .30-cal APM2 shots can be compared in ratio fashion to the .50-cal APM2 for a quick approximation of performance consistency. For the adaptive air gap factor, experiments were conducted at 3", 6", 9", and 18". Eighteen inches was selected as the maximum standoff because this distance still provided room for C17 transportability. The areal density range of an armor for this adaptation ranges from 63 psf at 3" to 33 psf at 18". This result is nearly a 50% reduction in the required areal density for defeat over the adaptive factor configuration range. For the three .30-cal APM2, the adaptive gap was set at 12". This resulted in a mean areal density for the three shots at approximately 28 psf. Through extrapolation, the required areal density for the .50-cal APM2 at this same air gap was approximated at 42 psf. Recall the adaptive mass areal density range for complete defeat was calculated at 48 psf and 80 psf for the threshold and objective threats, respectively (see Tables 5 and 6). The 28 psf and 42 psf areal density ratios for adaptive air gap were consistent with the 48 psf and 80 psf. Had these ratios been significantly different, additional investigation would have been required to understand the ratio disparity.

For the adaptive obliquity factor, experiments were conducted at 0°, 30°, and 60°, all at the maximum standoff of 18". The areal density for total threat defeat ranged from 34 psf to 18 psf, respectively, for the 0° to 60° range of obliquities. These adaptive factor configurations provided an additional 50% reduction in required areal density for complete threat defeat over the range of adaptive factor configurations. This finding shows how nesting of adaptations can provide a cumulative benefit in system performance and therefore resilience.

d. Combinatorial Effects of Adaptive Factors

By having three configurable factors (mass, obliquity, air-gap), the user has three degrees of freedom to be able to modify, reconfigure, or more appropriately, “adapt” the armor system toward achieving a desired functional outcome—stopping the threat. Thus, far, the configuration space has been identified but not the specific configurations that reach the

desired output. Additionally, the hypothetical functions only represent one end of the functional configuration space, the penetration resistance. The converse of this adaptability problem is that these adaptations could have implication (positive or negative) elsewhere on the armor system or overall vehicle system. In order to characterize the factors fully, additional analysis may be required to assess the second-order implications of the factors on the overall functionality of a system. For example, mass always helps in penetration resistance, but if the armor weight makes the overall vehicle system too heavy, the functional benefit sought may not be worth the negative implication on other system aspects.

Combined factor inputs may have a positive or negative synergistic effect on the higher functional output. Sometimes these combined factor configurations have an additive effect, in which the output is purely a summation of the inputs. Sometimes the factor inputs have a less-than-additive effect on the combined output, in which the individual factor outputs or responses are not cleanly additive. Often, the combined factor inputs can have a synergistic effect on the combined output, resulting in an overall output greater than the sum of the individual factor outputs. The outcome is that the factor configuration must be looked at in a combined fashion to see its ultimate cumulative effect on the desired functional output. Referring back to Figure 57. , the obliquity experiments were conducted at the maximum standoff of 18", the maximum air gap adaptation. By adding obliquity to the air gap, additional ballistic performance was achieved. In other words, a cumulative ballistic benefit was realized by combining the factors. This means that the protection of the armor could extend past the objective threat protection and provide extended protection against higher performing ballistic threats. This benefit could also be used to optimize the mass of the armor system against the specified threats in the requirement. This concept refers back to the two different ways to utilize adaptive capacity discussed in Chapter II.

e. Summary of Adaptive Factor Characterization

Characterization of the factor configuration solutions is a critical step to the MSIAR methodology. In this step in the methodology, the system user gathers the data and defines the scope or range of adaptability that can be achieved for the factor configurations of interest and shows how those adaptations can assist the user obtain higher performance from the

system. The output of this step is a comprehension of each factor's effect, and perhaps its combinatorial effect, on the final performance of the system.

Developing an adaptive armor system requires analysis of the ballistic limits for rolled homogenous steel armor plate. It was identified previously that at the very least, an RHA areal density of 24 psf and 40 psf were required for the threshold and objective threats, respectively. Recall that these metrics were doubled to 48 psf and 80 psf in order to ensure that the threshold and objective threat would be defeated. These values can be viewed as the benchmarks the adaptive system areal density must meet (as light or lighter in areal density). Any adaptive armor defeating this threat set at lighter areal densities would be demonstrating efficiency and benefit over a traditional static armor in achieving the identified performance specification, realizing the target KSAs and KPPs, and meeting the specified operational requirements listed in the draft GCV CDD.

The remaining adaptive factors of dimensionality and dynamic state show important effects on achieving the desired specification, attributes, parameters, and requirements as well. Characterization data were not collected for dynamic state but will be touched on in the following steps. Characterization data were collected on dimensionality. Dimensionality of an armor affects the ballistic protection performance of the armor and therefore can have an effect on the mass of the armor and the GCV. As previously demonstrated, the more volume an armor has, the better its ballistic performance. However, if an armor is dimensionally doubling the width of the GCV, it will violate other requirements, particularly the mobility and transportability requirements. Therefore, an armor with an adaptive dimensionality could be highly valuable for all the specified requirements.

Through experimentation, it was shown that a quarter-inch piece of MIL-DTL-41600E steel plate coupled with MIL-DTL-32262 aluminum plate separated by an adaptive air gap achieved significant ballistic mass efficiency. Table 7. shows the areal densities achieved at the smallest and largest air gaps. Additionally, areal density ranges associated with an 18-inch air gap and a range of obliquity of 0° to 60° are also shown. Mass efficiencies greater than 2 can be realized through simple dimensionality adaptations. The benefit of these adaptations is that the volume penalties that a user would pay at the highest dimensional values can be eliminated as quickly as they were created. An armor with an 18-

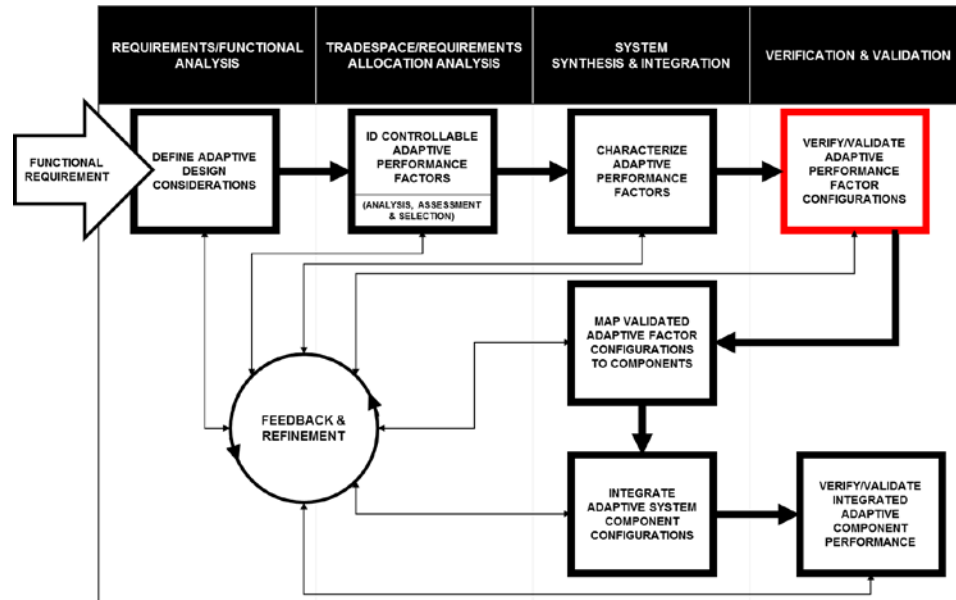
inch air gap extending from both sides of the GCV would not be ideal for loading and transporting on a C17. It would also severely restrict the mobility corridors the vehicle is required to traverse, particularly in urban environments. However, with an adaptive air gap, the user can have the protective benefits of an 18-inch air gap when the situation dictates, and when the user needs transportability or mobility, the air gap can be reduced back to 3 inches, giving back the mobility needed for other aspects of mission success.

With two of the three adaptive factors characterized, this step of the MSIAR is complete. The third adaptive factor will emerge after step 4 of the MSIAR. The next step is the verification and validation of the characterized adaptive factor configurations.

Table 7. Adaptive Factor Ranges and Required Protection Areal Densities

Adaptive Factors:	Adaptive Range:		Mass Efficiency vs. (RHA V ₅₀)	Mass Efficiency vs. (RHA 2(V ₅₀))	Remarks:
	Minimum Required Areal Density (psf)	Maximum Required Areal Density (psf)			
Mass:	RHA V₅₀	RHA 2(V₅₀)	E_m	E_m	¹ Extrapolated approximations from experimental data points collected at 12" air gap. Extrapolation used the same adaptive plot slope as the Objective response curve. ² Minimum adaptive range value based on the maximum adaptive range extrapolated value from Air Gap adaptive factor data. Both are 0° obliquity. Threshold maximum value will not exceed the Objective maximum value, therefore Objective value is used.
Threshold	24	48	1	1	
Objective	40	80	1	1	
Dimensionality:					
Air Gap: HH-AL	18"	3"	E_m	E_m	
Threshold	28 ^[1]	38 ^[1]	0.85	1.7	
Objective	33	63	1.21	1.26	
Obliquity: HH-AL	60° (@18" AG)	0° (@18" AG)	E_m	E_m	
Threshold	<17.5 ^[2]	28 ^[2]	>1.37	1.7	
Objective	17.5	33	2.28	2.42	
Dynamic State:					
Threshold	?	?	?	?	
Objective	?	?	?	?	

4. Verify and Validate Adaptive Performance Factor Configurations



Step 4 of the MSIAR seeks to answer two questions. Do these characterized configurations achieve this adaptive range of performance? Are these the correct adaptive performance factor configurations to achieve the desired adaptive resilient armor system?

Figure 58. Step 4: Verify/Validate Adaptive Performance Factor Configurations

Figure 58. depicts step 4 of the MSIAR. Verifying and validating the resultant factor configuration solutions is critical to being able to predict accurately or even approximately the outcome of a system's adaptation. Each factor has its own effect on the adaptive functionality. Sometimes these effects are independent of the other factors, sometimes they are not. As previously discussed, the factors can have additive or linearly-cumulative combinatorial effects. Sometimes effects conflict where, individually, two factors have a positive outcome on a functional output, but when combined, have a negative output. Often, synergistic effects occur in which the combined output of the two factor functions is greater the sum of the two outputs. Because of this resultant inconsistency, verification and validation of the resultant factor configuration solution must be conducted. This process generally consists of a series of tests to collect data and build a statistically significant level of confidence in the identified adaptive factor performance at the range of adaptive factor configurations.

In the previous step, experiments were conducted for factor characterization. These characterization efforts can be associated with experiments and tests that would occur at system technology readiness level (TRL) 1–3. Verification and validation testing in this step of the methodology would be akin to TRL 3–5. For the adaptive armor system example that has been discussed so far, it would involve expanding armor testing at the various dimensional, dynamic, and mass states to acquire relative performance measurements. This level of testing and experimentation could not be conducted for this dissertation because of time and resource constraints. Therefore, a limited series of experimental test results will be used to continue to develop the proof for the MSIAR.

Verification and validation need not occur at each configuration state. For the two-dimensionality adaptive factors that were characterized, the adaptive ranges of interest were 0° to 69° and $0''$ to $18''$ for obliquity and air gap, respectively. Dividing these factor ranges to whole-number design points (7 and 5) would require 35 experiments to obtain a data point at each design point. The tester would then multiply this by multiple tests to build statistical confidence in the data; it becomes readily apparent that testing can become very intensive. This is where design of experiments (DOEs) can be of great value. Through proper analysis, a full factorial test set can be reduced to a half factorial or even lower and still acquire the statistically relevant and confident data to verify and validate the performance of the system and performance factors. Figure 59. shows an example of how DOEs can be used to reduce experiment sets while maintaining an experiment design that gathers hard cumulative functional output values to compare, contrast, and verify or deny the formulaic characterization data from the previous step. Using proper design of experiments methods, an appropriate fractional factorial verification experiment set can be assembled to generalize the holistic functional response at the various factor configurations. If significant discrepancies exist between the predicted functional output and the experimental output, a causal investigation can be conducted to characterize more accurately the factor correlation on the functional output.

DOE: FF		Obliquity				
		0°	15°	30°	45°	60°
Air Gap	0"	X	X	X	X	X
	3"	X	X	X	X	X
	6"	X	X	X	X	X
	9"	X	X	X	X	X
	12"	X	X	X	X	X
	15"	X	X	X	X	X
	18"	X	X	X	X	X

DOE: HF		Obliquity				
		0°	15°	30°	45°	60°
Air Gap	0"	X		X		X
	3"		X		X	
	6"	X		X		X
	9"		X		X	
	12"	X		X		X
	15"		X		X	
	18"	X		X		X

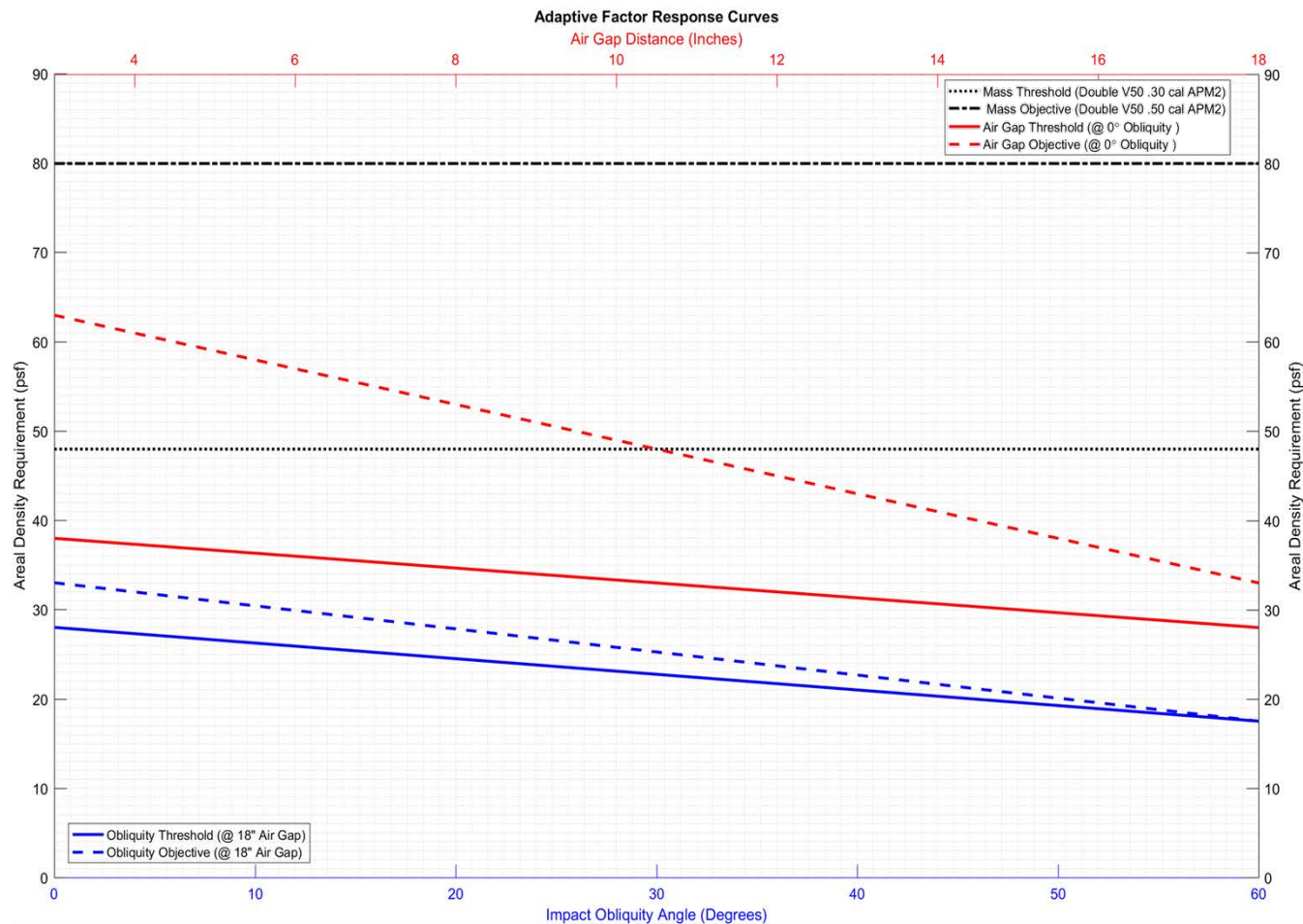
DOE: RF		Obliquity				
		0°	15°	30°	45°	60°
Air Gap	0"					
	3"	X		X		X
	6"					
	9"		X		X	
	12"	X				
	15"					
	18"	X		X		X

This figure shows how employing design of experiments (DOEs) can reduce the test and experiment load so that iterative tests can be conducted to build statistical confidence to verify and validate functional performance. Adaptive factor performance trends could be easily derived from the reduced factorial DOE on the right, which could be just as informative as the full or half factorial. This reduced set is less resource-intensive, which can allow more tests to be conducted for greater statistical confidence at similar cost, compared to the cost of the higher factorial DOEs.

Figure 59. Full, Half, and Reduced/Fractional Factorial DOE.

Once function outputs are verified (and potentially adjusted), the output values must be validated and reconciled against the original adaptive design considerations that were specified in the first step of the methodology, as shown in Figure 60.

Validation ensures the adaptive functional requirements are actually met or achieved. If gaps exist between the requirements and the resultant configuration outputs, they must be filled. This can be done through further experimentation by adding additional factors, expanding the factor state range, or if the requirement cannot be met, informing the stakeholders of the situation and proposing a change to the requirement.



This graph depicts the residual plate penetration of the threshold and objective threats into MIL-DTL-32262 aluminum plate after striking various obliquities and air gaps of a .25" plate MIL-DTL-41600E steel. Data on such an armor target at adaptive obliquity and air gaps design points do not exist. Therefore, limited experimental test were conducted to characterize such an armor system. This data collected in step 3 of the MSIAR will serve as the output of step 4 and be used for informing decisions on step 5.

Figure 60. Integrated Adaptive Factor Response.

Based on the limited experimentation conducted in the previous MSIAR step, the experimental adaptive factor performance data shown in Figure 60. will serve as verified and validated adaptive factor-performance response curves. These response curves will be included in the next step of the MSIAR to aid in identifying adaptive components and subsystems, which will serve as the physical means to achieve the desired adaptive system performance. Figure 61. depicts a summary crosswalk of the adaptive factor configuration ranges which will address the respective adaptive design considerations shown on the right side of the image.

Adaptive Factors:	Adaptive Range:		Mass Efficiency vs. (RHA V_{50})	Mass Efficiency vs. (RHA $2(V_{50})$)
	Minimum Required Areal Density (psf)	Maximum Required Areal Density (psf)		
Mass:	RHA V_{50}	RHA $2(V_{50})$	E_m	E_m
Threshold	24	48	1	1
Objective	40	80	1	1
Dimensionality:				
Air Gap: HH-AL	18"	3"	E_m	E_m
Threshold	28 ^[1]	38 ^[1]	0.85	1.7
Objective	33	63	1.21	1.26
Obliquity: HH-AL	60° (@18" AG)	0° (@18" AG)	E_m	E_m
Threshold	<17.5 ^[2]	28 ^[2]	>1.37	1.7
Objective	17.5	33	2.28	2.42
Dynamic State:			E_m	E_m
Threshold	?	?	?	?
Objective	?	?	?	?

ADC #1 & #2

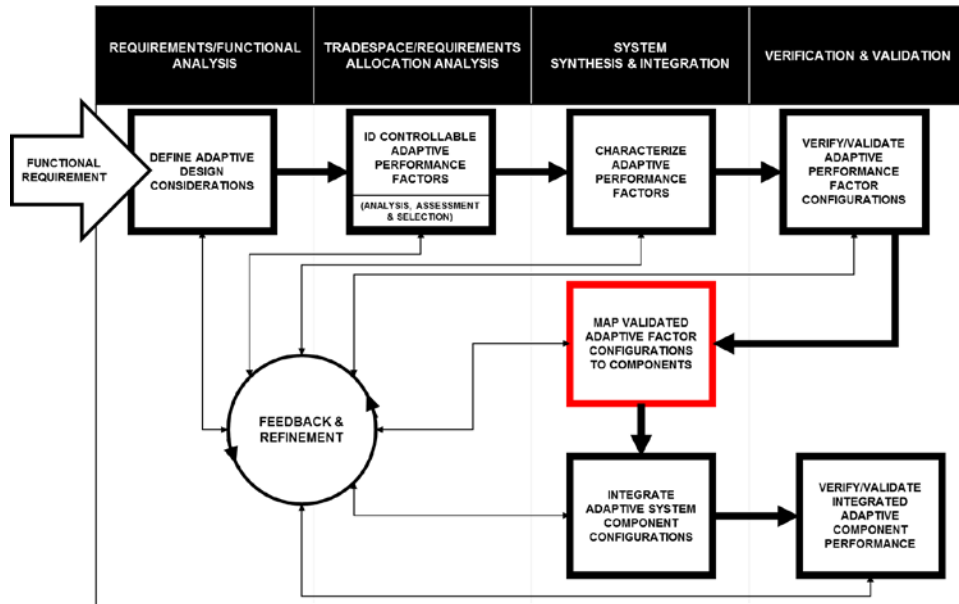
ADC #3

ADC #2

This figure depicts how the adaptive performance factors trace to the adaptive design considerations from Table 5. By adapting the dimensionality, 50% weight reduction (40 psf reduced to 17.5 psf) in armor areal density can be achieved, making these adaptive factor configurations suitable for Adaptive Design Considerations 1 and 2. Adaptive Design Consideration 2 is denoted in red because it is unknown how much weight can be removed from the design. This will be fully understood and optimized as the MSIAR is continued and more is learned about the dynamic state adaptive factor. The dimensionality adaptive factor also can support a total GCV vehicle width of 198". Adaptive Design Consideration 3 constrains the armor plus vehicle width to 204". The dimensionality adaptive factor can adapt from 3" to 18", allowing the vehicle to have the enhanced protection of the 18-inch armor standoff while being able to collapse to 3" for strategic transport.

Figure 61. Validated Adaptive Factor Response.

5. Map Validated Configurations to Adaptive System Components



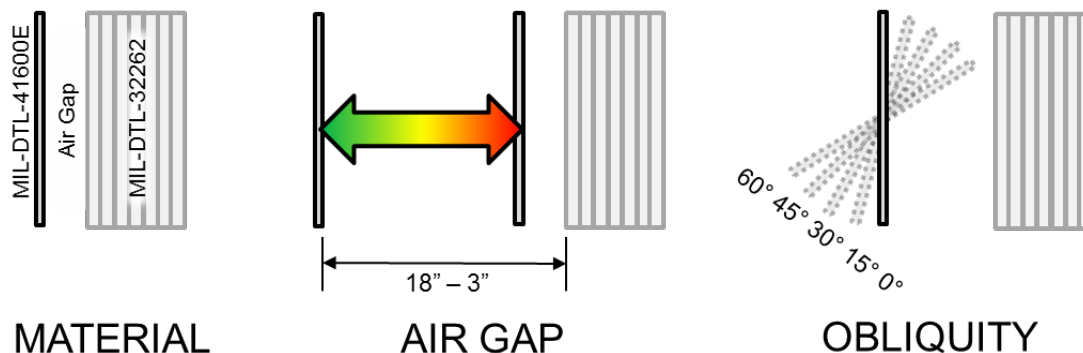
Step 5 of the MSIAR seeks to answer the following question: What physical component implementations achieves the verified and validated range of adaptive performance configurations?

Figure 62. Step 5: Map Validated Configurations to Adaptive System Components.

Figure 62. depicts step 5 of the MSIAR. Once the configuration solution outputs have been verified and validated against the functional requirements, the next step involves mapping the configuration solutions to physical subsystems and components capable of producing the configuration states and functional outputs. This step consists of identifying physical components that have the configurability to enable the overall system to operate at the identified adaptive factor configuration states. If subsystems or components do not exist with this capability, a design and engineering process must occur to create them or to integrate that capability into existing systems. In the characterization of adaptive performance configurations step of the MSIAR, factor characterization experiments were conducted to understand the benefits of having an adaptive obliquity and air gap in an armor design. The armor system used for the experiment was a simple quarter-inch of MIL-DTL-41600E steel plate coupled with a stack of MIL-DTL-32262 aluminum plates.

The adaptive obliquity and air gap was achieved through the manipulation of the steel plate to the air gap distance or obliquity of interest, as shown in Figure 63. This armor

structure is simple yet ideal for ballistic threats such as the .30-cal APM2 and .50-cal APM2. The high hardness of the steel front plate can fracture the threat, and the ductile aluminum absorbs the residual dispersed particles and energy. This will serve as a starting point for the adaptive design. However, this design still lacks a dynamic performance component. This is where novel armor called mechanically adaptive armor linkage (MAAL) could play a role.



This figure depicts the various experiments conducted to characterize the initial adaptive factor performance. The first image shows the standard material make up for each experiment. Each experiment has an effector plate made of high hard MIL-DTL-41600 steel, an air gap, and a stack of 8 MIL-DTL-32262 aluminum plates. The aluminum plates serve both as the catcher and as a residual penetration witness measure to understand the adaptive factor effects on the terminal ballistic performance of the armor system. The middle image shows how air gap dimensionality was adapted to achieve increase in terminal ballistic performance. The air gap was adapted between 3" and 18" to achieve various ballistic effects. The third image depicts how the obliquity was adaptive to achieve various threat-armor impact angles ranging from 0° to 60°. During the experiments, the threat would first strike the effector plate, react in the air gap, and then embed at various plate depths in the catcher/witness plates. The deeper into the witness the threat penetrated, the lower the effect of the adaptive armor design configuration. The shallower the residual penetration, the greater the effect of the adaptive armor design configuration.

Figure 63. Adaptive Factor Characterization Experiments.

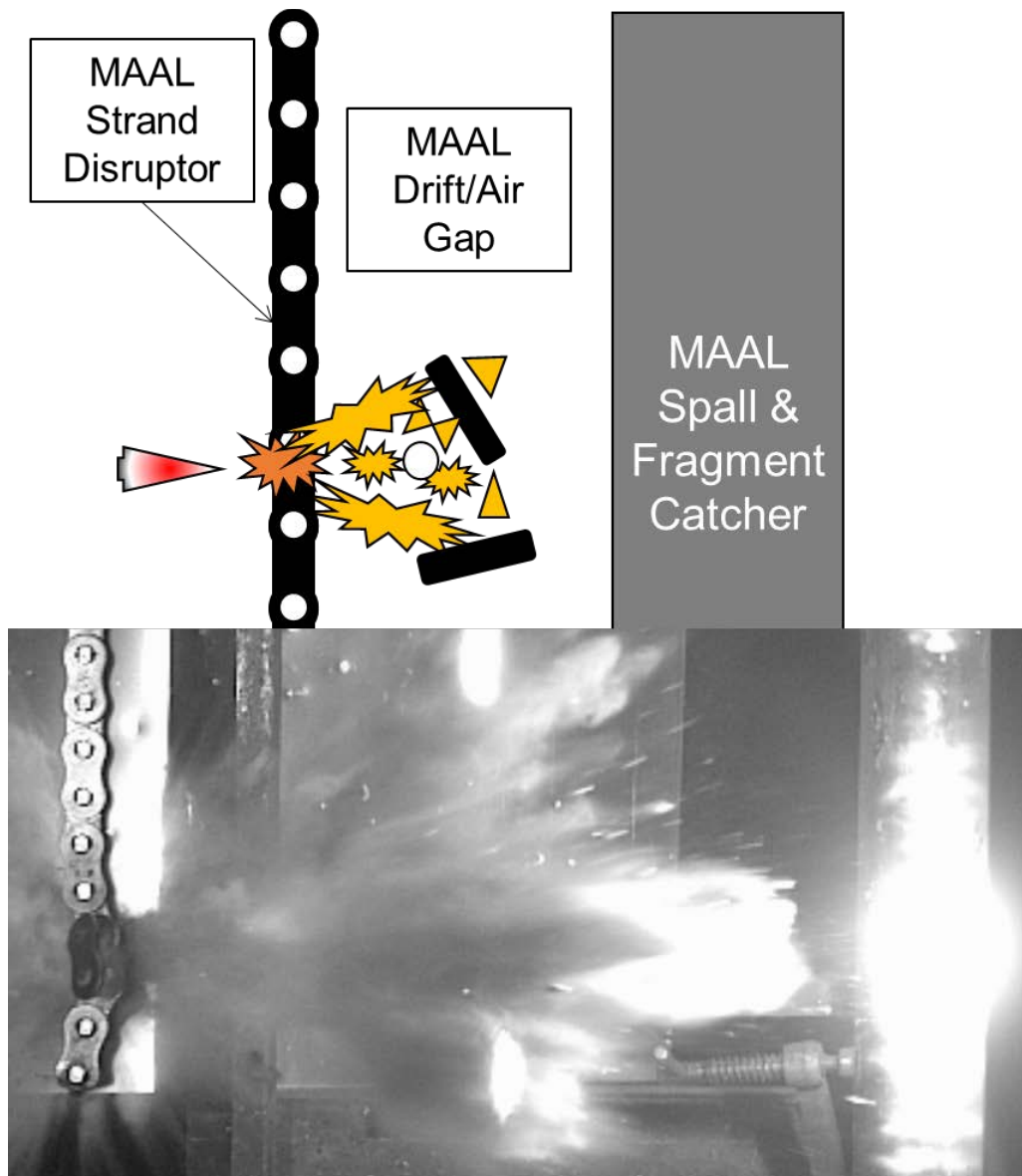
a. Mechanically Adaptive Armor Linkage (MAAL)

The MAAL armor system provides enhanced passive armor ballistic protection through passive dynamic deflection and ability to accumulate mass at the point of threat impact on the armor strike-face. The MAAL armor system causes a yaw effect on ballistic threats because of reactive tension in the MAAL armor strands acting on the threat and after impact with the threat. Because of the dynamic capacity in the fundamental link structure, the MAAL armor can also be implemented through numerous embodiments. Because of these

features, the MAAL armor system will be the first component mapped to the adaptive armor system.

The MAAL system contains three basic components, as shown in Figure 64. The MAAL strand disruptor consists of either the band or link strand (bike chain or similar structured material), which is hanging in tension. This strand through its structure must passively deflect upon threat impact and absorb the threat energy through spallation, fragmentation, and plastic deformation. Structurally, the MAAL air gap provides the disrupted MAAL strand and threat particles volume to disperse and expand. This can be composed of air or any low-density material, such as Styrofoam, for example. The MAAL spall and fragment catcher serves structurally as a dispersed particle catcher, absorbing all residual energy through inertial transfer from the disrupted and dispersed MAAL and threat particles.

This structure is similar to the steel spaced armor that was characterized through ballistic experimentation. The major difference is that instead of a rigid high hardness steel plate, a dynamic strand of very high hardness steel with one degree of rotational freedom is used. This raises the question, would this flexible structure offer as much kinetic energy dissipation as a rigid plate? This is a hard question to answer. A good answer that can be supported with experimental results is that the plate on average absorbs more kinetic energy (see Appendix B). However, the strand and its dynamically enhanced structure wreaks havoc on the kinematic stability of the projectile, causing it to tumble, yaw, and deform in a fashion that makes its resultant impact and penetration on the catcher less than ideal. This is shown in Figure 65.



This figure depicts the system structure and operation of the MAAL armor system. MAAL armor consists of three components: the MAAL strand disruptor, the MAAL drift or air gap, and the MAAL spall and fragment catcher. Each of these components of the MAAL armor system serves a critical function in the terminal ballistic performance of a MAAL armor. When the threat strikes the MAAL strand disruptor, projectile energy is absorbed in the fracture of the MAAL strand into fragments. This disruption also causes the threat projectile to yaw, pitch, and tumble, which in turn decreases its energy and penetration. The air gap allows this disruption to take effect. The greater the air gap, the greater the disruption. The air gap also disperses the residual MAAL fragments and threat particles, dispersing their energetic impact over a greater area on the fragment catcher. The high-speed photograph at the bottom of the figure clearly shows the disruption, dispersion, and impact of the MAAL and threat interaction.

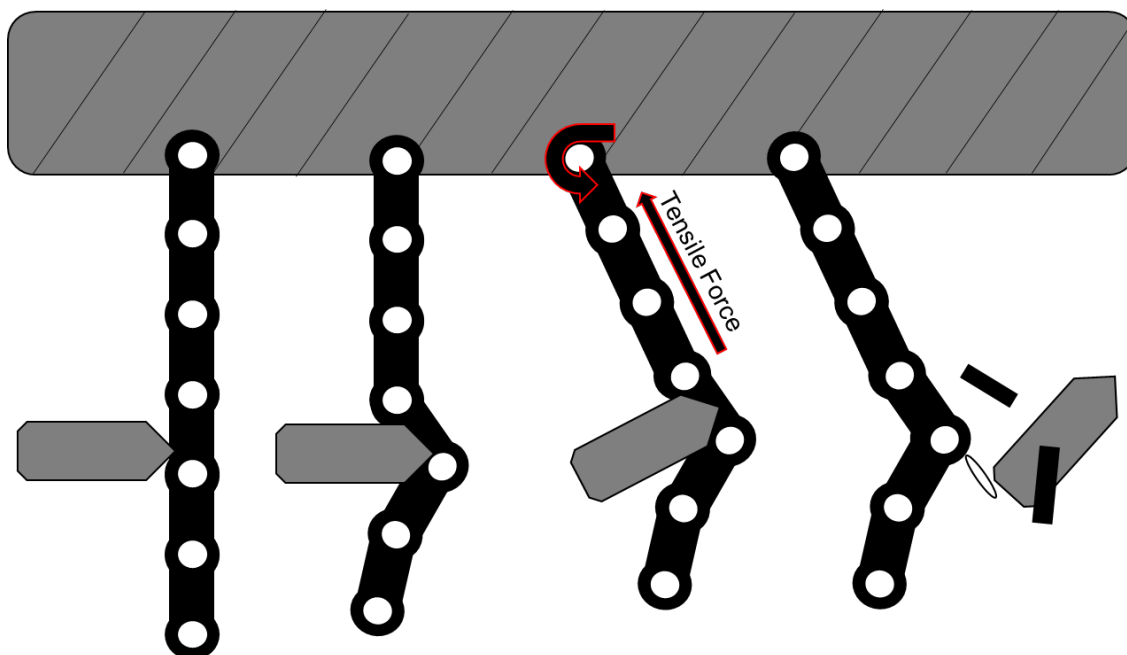
Figure 64. Mechanical Adaptive Armor Linkage System Structure.



This figure depicts a threat–MAAL interaction. The pitch and yaw of the projectile caused by the strand disruptor is clearly shown. This impact angle significantly decreases the threat’s ability to penetrate into the catcher phase of the armor. The particle cloud and fragment impact on the catcher clearly show particles that were placed into motion by drawing energy from the threat projectile upon its impact with the disruptor.

Figure 65. MAAL Strand and Threat Interaction.

Non-ideal impacts reduce the depth of penetration, and subsequently, the required areal density required for protection. This occurs through a pendulum effect occurring at the point of impact. The threat and the strand elastically collide and travel together for brief moment until the tensile strength of the MAAL strand pulls and accelerates the strand and the elastically bonded threat toward the strand’s pivot point. This is depicted in Figure 66.



This figure is a cartoon depiction of how threat–MAAL interactions occur. The pitch and yaw of the projectile caused by the strand disruptor is clearly shown. Upon impact, the threat displaces and plastically deforms the MAAL strand. During this interaction, the strand travels a distance with the threat, but in doing so, the interaction zone travels in a radial fashion because the MAAL strand is typically pinned at one end. This radial travel path of the threat–MAAL interaction point applies a tensile force on the threat, creating a yaw or pitch on the body of the threat. This serves as a disruption to the threat, greatly reducing its subsequent ballistic penetration into following materials. Adapted from Cannon (2015).

Figure 66. Threat Pitch and Yaw Interaction with MAAL Strand.

At this point, the impact converts to an inelastic impact, and the material deformation begins absorbing energy and disrupting the threat’s kinetic energy, similarly to the rigidly fixed armor plate. This threat–MAAL interaction possesses both benefits of plastic deformation of the rigid plate, and trajectorial disruption caused by its shifting dynamic state.

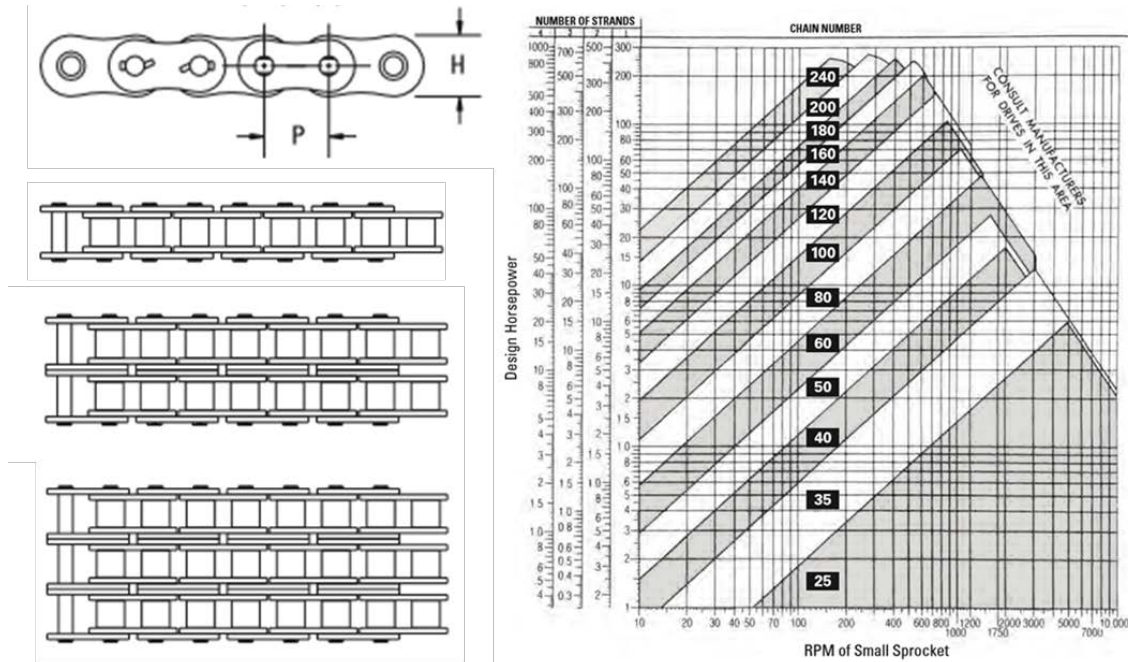
b. Mapping Components to the Dynamic State Adaptive Factor

In the previous steps of the MSIAR, the dynamic state adaptive factor was not characterized in detail because this adaptive factor is highly dependent on the material makeup of the armor. A generalized but meaningful characterization could not be made with the resources available for this research. The only meaningful characterization that could be made was based on a simple conservation of energy analysis in which any dynamic state (not fixed) would have an effect on the terminal ballistic performance of the armor. Now that a

specific armor structure has been selected, analysis of its dynamic state can effectively occur. In the previous paragraph, it was shown that the MAAL system employs dynamic behavior and state in its ballistic defeat mechanism; the fixed plate armor did not. This means that there is room for adaptation within the dynamic state.

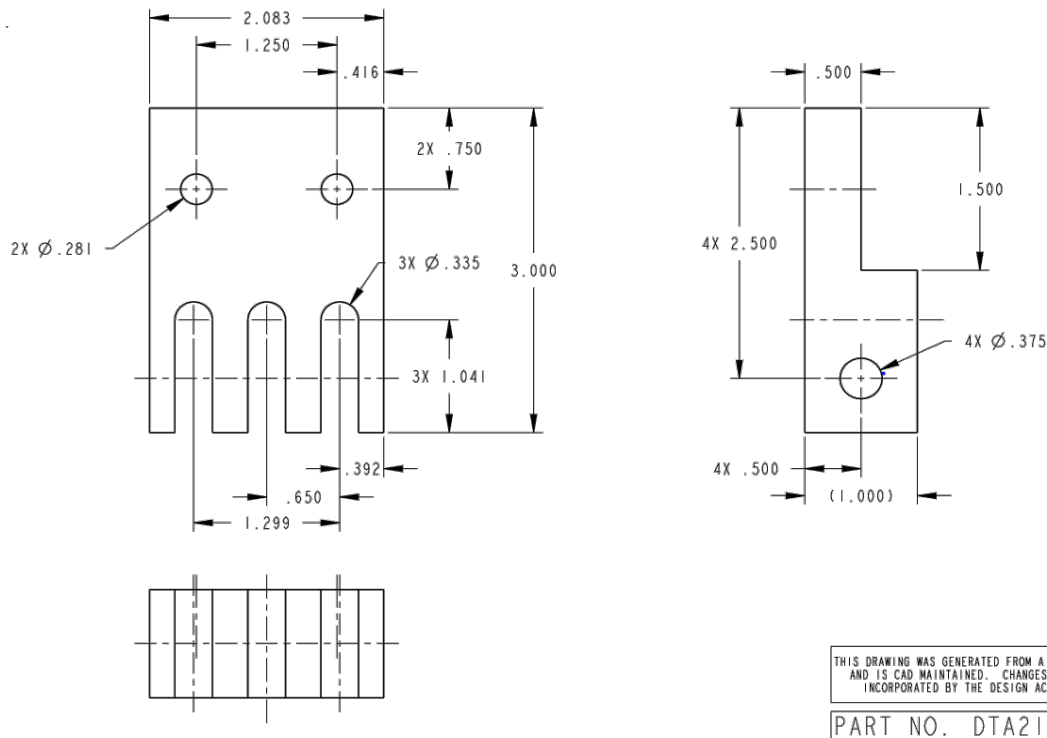
This adaptation can occur through the moment inertia of the MAAL strand. Because this adaptation is targeting the inertial properties of the MAAL strand, it is technically employing two adaptive factors: the dynamic state and the mass of the MAAL armor. Because no specific dynamic state adaptive factors exist outside of this, the inertial properties adaptation will subsequently be considered only a dynamic state adaptive factor. MAAL link strands are essentially roller chains or leaf chains. These chains (MAAL strands) are manufactured and commercially available in various sizes, thicknesses, and widths and therefore offer a variable moment of inertia with each size, thickness, and width. Figure 67. shows the numerous and various size and masses of commercially available MAAL strands. If the commercially available strands do not meet requirements, specifically designed and optimized strands can be manufactured with relative ease.

The ease of manufacture means that the MAAL dynamic state ballistic defeat mechanism can be adapted based on the size of chain used in the armor. This adaptation is truly manipulating the dynamic state of the armor for ballistic performance benefit. Although the availability of the chain enables this dynamic state adaptive factor, more components must be mapped to achieve true efficiency. Each MAAL strand size depicted has a different link interface that must be matched to allow the strand to hang in tension. Therefore, a design process for the link range of interest must occur. Figure 68. shows the interface adaptor component that must accompany each MAAL strand size (25 to 240).



This figure shows the simplex, duplex, and triplex strands that can have link plate pitch (P) and height (H) varying from .5" to over 3". The graph on the right side of the figure shows that chains (MAAL) are readily available from sizes 25 to 240, which cover the pitch/height range of .5" to 3", respectively. Each size and -plex of chain will have its own inertial characteristics. This gives MAAL an adaptive range of inertial states that can be scaled in an external reconfiguration adaptation mode to achieve an adaptive resilient state in the armor design. Source: Timken Drives LLC (2013).

Figure 67. MAAL Strand Sizes.



This figure shows design drawings with dimensions for the MAAL interface adaptor, which allows external reconfiguration of redundant and progressive scaling of the MAAL strands. These adaptors mesh with the knuckles of the MAAL strands allowing variable strand sizes to apply to an armor system rapidly to accommodate changing operational requirements.

Figure 68. MAAL Strand Interface Adaptor.

c. Mapping Components to the Mass Adaptive Factor

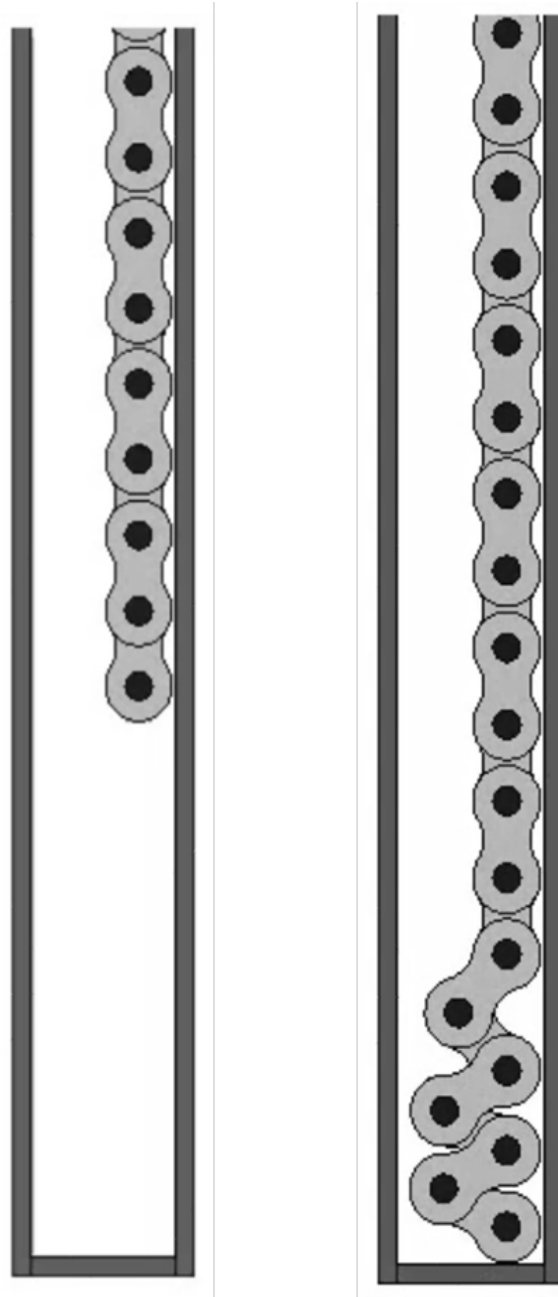
Mass is the most influential of the adaptive factors. Mass adaptation can occur through both external and internal reconfiguration modes of adaptability. External reconfigurations of mass include the progressive scaling and redundant scaling of the strand mass. The internal reconfiguration of the mass strand occurs through reallocation. These modes of adaptation will be mapped to components in the following paragraphs.

Progressive and redundant mass scaling component mapping is simple because they both are developed from components designed for the dynamic state adaptations. Progressive mass scaling is achieved in the same fashion as is the inertial dynamic state adaptation. Changing the size of the MAAL strand changes the mass and ballistic performance of the strand. The strands inertial properties and dynamic state also change. The MAAL strand

adaptor serves as the same component used for enabling the progressive scaling adaptation. Redundant scaling is a bit different. Redundant scaling is achieved by adding the same-sized strand to the existing strand. For example, if an armor system employs a single size-40 MAAL strand but needs additional ballistic performance for new threats, adding another size-40 strand would be considered a redundant scaling of the mass for the armor system. This adaptation is achieved through the same MAAL strand adaptor shown in Figure 68. However, each additional strand requires its own adaptor. This means that the fastener that attaches the adaptor to the greater vehicle armor system structure must account for this added length and load.

Mass reallocation component mapping requires pulling the same factor resources from elsewhere in the system to apply them toward the disrupted functional requirement. For an adaptive armor, this would require pulling armor mass that is not ballistically engaged elsewhere in or on the vehicle armor system and applying it where the armor is failing to meet the requirement. Implementing this goal with armor has been previously unachievable because armors have been structurally fixed and therefore not moveable. Even if an armor could have been moved, no effective method existed to move such a heavy mass in an operationally relevant fashion. This movement could be achieved in an externally reconfigurable fashion; however, this would not make sense because this would create a vulnerability in the armor protection that would require another external reconfiguration to fix. The key component in a MAAL armor system is the strand. The strand, whether a belt or linkage, is designed to move at very high speeds. If a MAAL strand was held at one end vertically in the air and then lowered to the ground, the linkages would pile up on top of each other, accumulating mass in that pile, as shown in Figure 69.

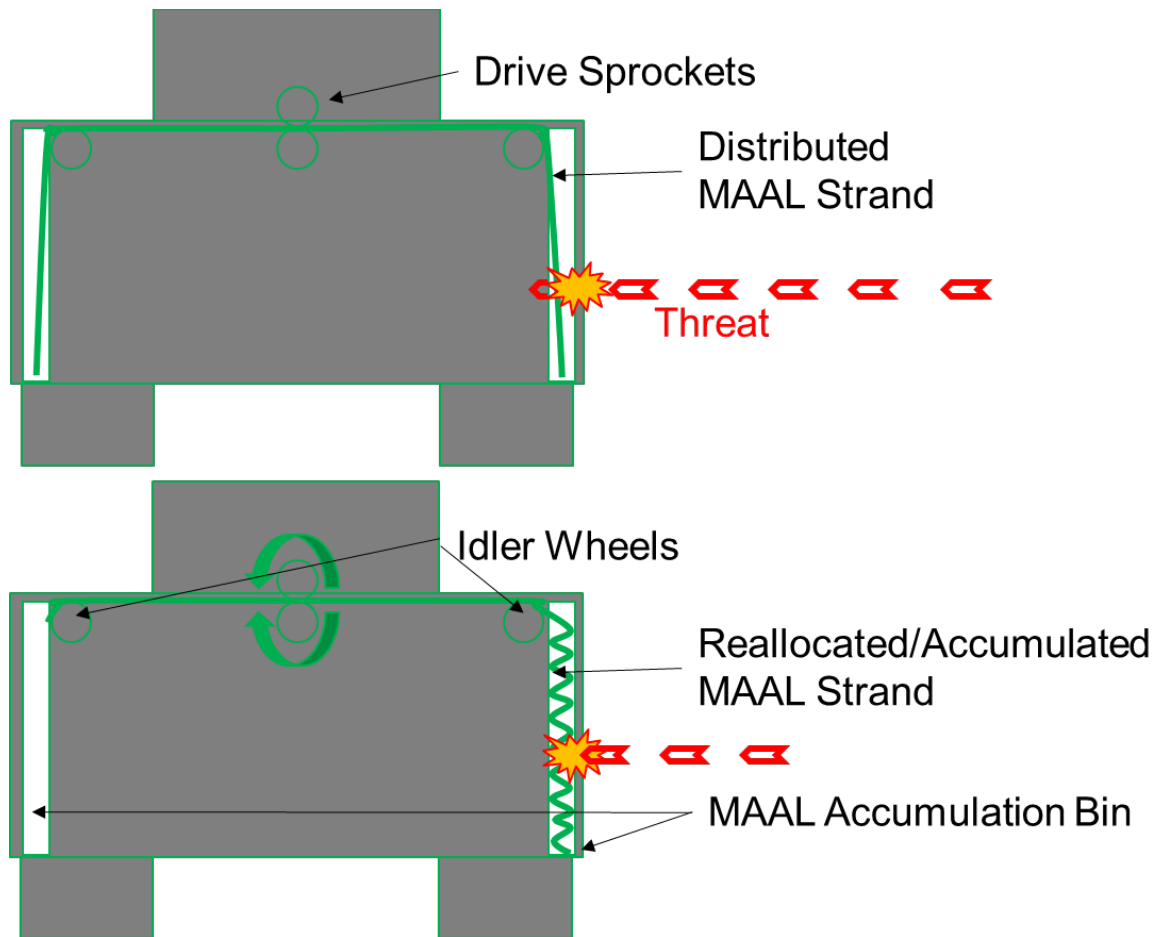
This aspect of the links structure can be harnessed as a way to manipulate the mass of the armor. Components to achieve this adaptation include sprockets and idler wheels, a drive sprocket, and MAAL collection bin. Figure 70. shows conceptually how these components would work to achieve the enhanced ballistic protection state needed for the system to achieve adaptive resilience state.



MAAL strand can pile up in a confined space to provide added mass to an area. This can be used to economically apply MAAL over a volume and then reallocate the mass of the MAAL as needed from nonthreatened areas to areas of concern or armor failure in situ.

Source: Cannon (2015).

Figure 69. MAAL Strand Mass Accumulation.



This figure depicts an alternate embodiment of MAAL. MAAL strands are derived from chain. Chains are designed to rotate and travel along cogs and gears. This purpose is modified to enable MAAL strands to be internally reconfigured through reallocation from areas that do not require protection to reinforce areas where protection is needed in situ
Source: Cannon (2015).

Figure 70. Operational View of MAAL Strand Mass Accumulation.

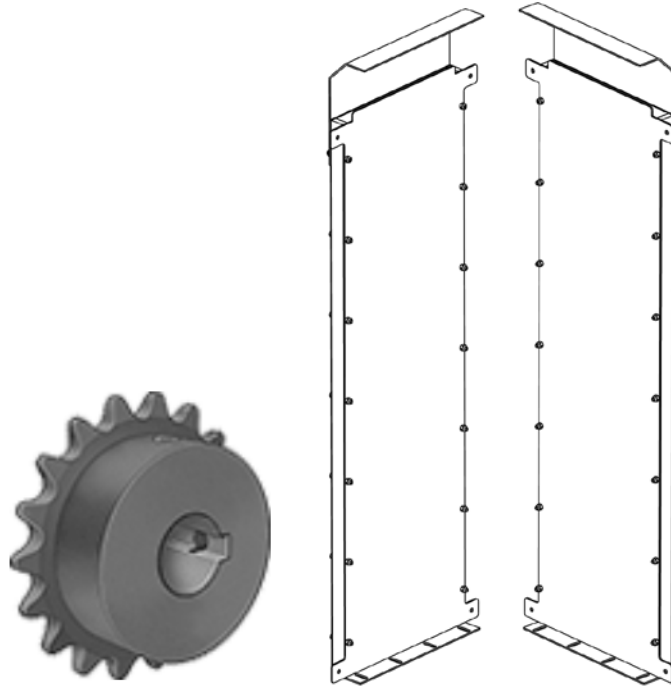


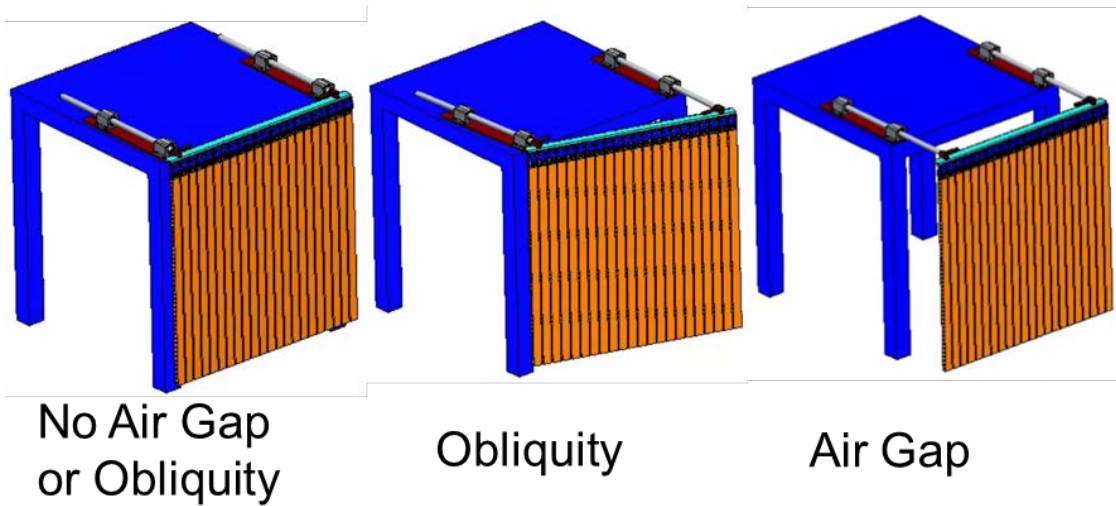
Figure 71. Mass Accumulation Sprocket and Collection Bin Components.

d. Mapping Components to the Dimensionality Adaptive Factor

Manipulating the dimensionality of the armor system is the easiest and most obvious of the three adaptive factors. The benefits of this adaptation were shown through the armor air gap and the obliquity phenomena. Components that enable this must be able to create the armor air gaps and obliquities that provide the needed adaptive capacity and fall within the requirements associated with the adaptive design consideration.

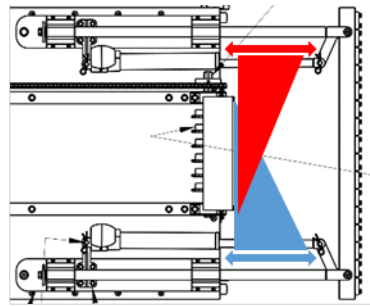
The components that achieve the air gap and obliquities must also be able to measure the weight they add to the armor system. They must have the agility appropriate to manipulate the armor and the structural rigidity necessary to support the armor, yet be lightweight enough to realize the benefits of the obliquity and airgap. This can be achieved using a lightweight actuator and structural linear bearings and shafts, which can both move and support the load of the MAAL armor. Figure 72. and Figure 73. show representations of these components. Some components will need to be designed and fabricated because they do not exist. This is a given for any technology integration: Some components exist, and others must be created to suit the required purpose. The dimensionality components provide a

sampling of both, created and available components. The actuator/bearing shaft coupler had to be created specifically for this purpose. This component brought together the driving force of the actuator and the structural rigidity of the linear bearing and shaft. These components enable the armor system to extend and collapse, thus creating the enhanced ballistic protection needed to achieve the adaptive resilience state.

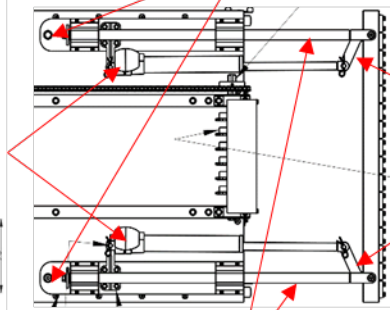
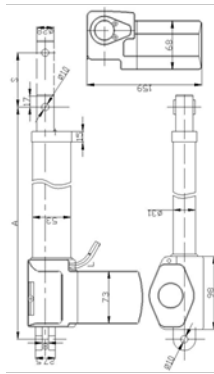
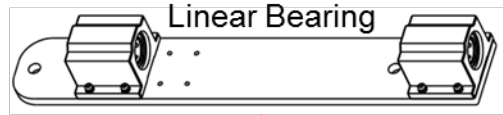


The three images show the initial design for achieving the obliquity and air gap adaptive factor configurations. The far left image shows the adaptive resilient armor system in its least-protected state, which also allows the mobility and strategic transportability requirements for the armor's host platform to be met. The middle and far right images show the enhanced protective states that achieve the protection requirements for the host platform.

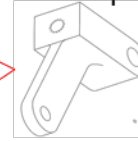
Figure 72. Armor Dimensionality States.



Components for Dimensional Air Gap and Obliquity



Actuator/Bearing Shaft Coupler



This figure depicts the components mapped to achieve the air-gap and obliquity adaptive factor configurations. The linear bearing, structural bearing shaft, and the actuator/bearing shaft coupler provide mobile structural support for the adaptive armor weight. The actuator provides motive force to the shaft to enable the internal reconfigurations to occur.

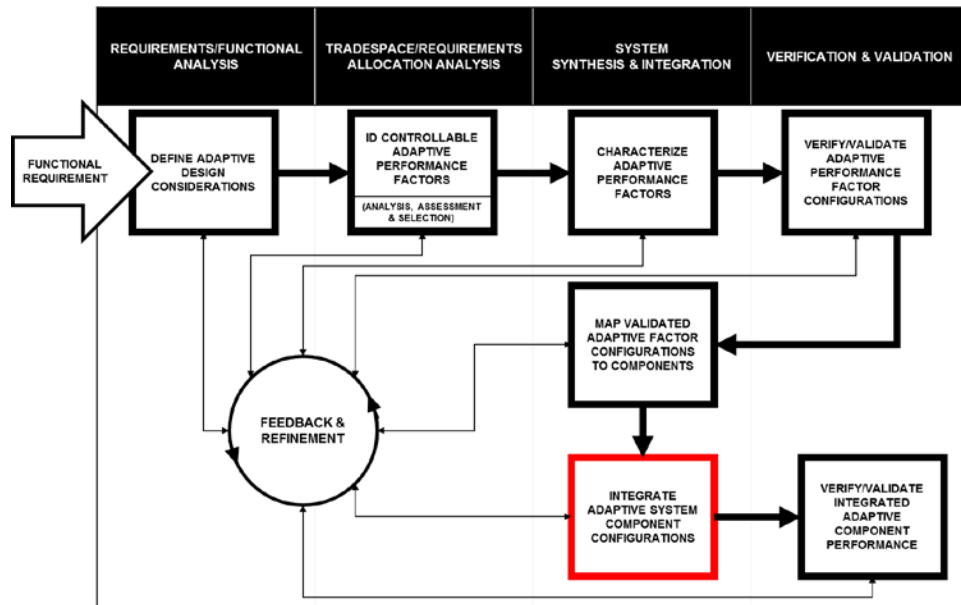
Figure 73. Armor Dimensionality Components.

e. Component Mapping Summary

Once the mapping of requirements to physical components is complete, the component performance at the various factor levels must be integrated, verified, and validated to confirm the predicted outcomes found in the characterization-model validation and verification. The components mapped in this phase of the methodology will enable the achievement of the adaptive design points that make this armor adaptive resilient. Although many components lead to the adaptive resilient armor, only key components were discussed to keep the focus on the salient aspects of this step of the methodology. The dynamic state

adaptive factor was mapped to the MAAL armor, which can be readily changed and scaled through the use of an interface adaptor bracket. The mass adaptive factor was achieved through accumulation of MAAL where the armor protection is needed. This was achieved through the use of drive sprockets, idler wheels, and the accumulation bin. The dimensionality factor was mapped to structure components such as a linear bearing. These components all enabled adaptive resilience to be realized in the armor system.

6. Integrate Adaptive System Components and Configurations



Step 6 of the MSIAR seeks to answer the following question: How do these physical components mesh into a cohesive functional system that provide cumulative or synergistic outputs?

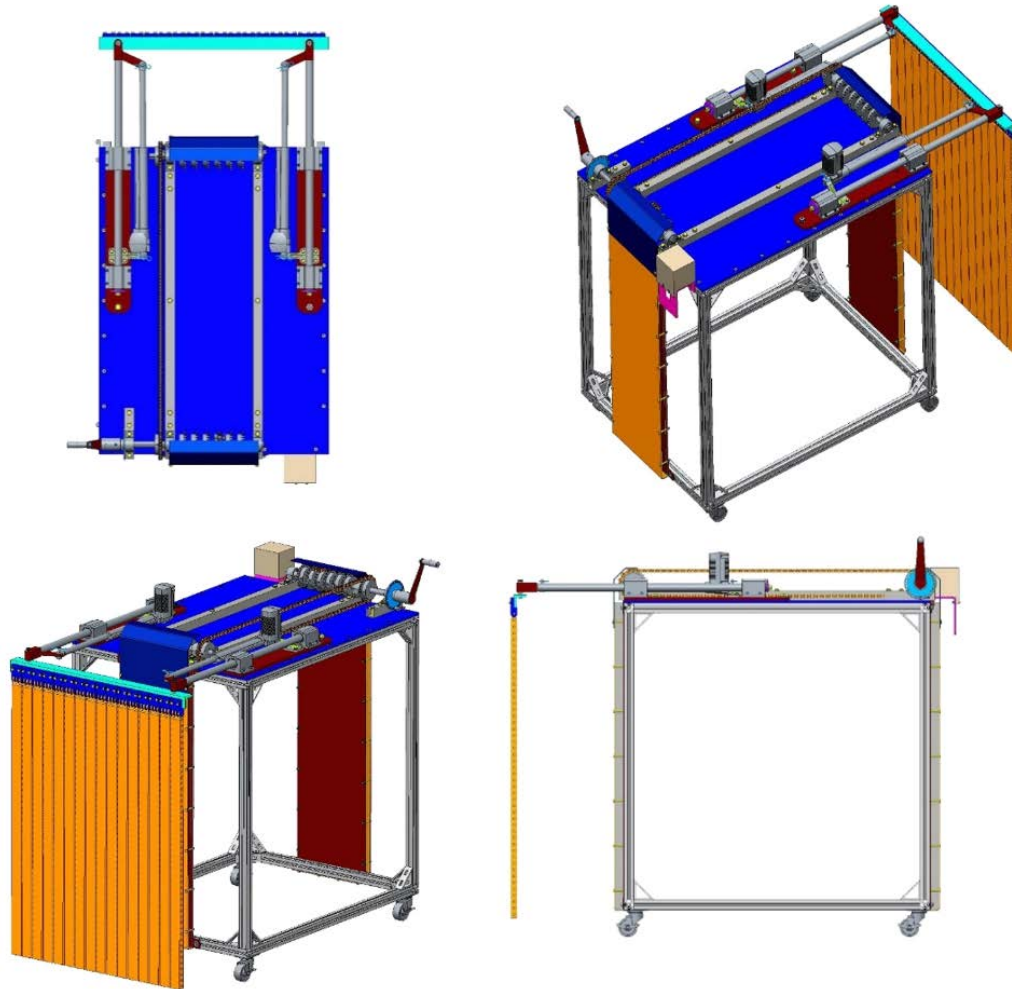
Figure 74. Step 6: Integrate Adaptive System Components and Configurations.

Figure 74. depicts step 6 of the MSIAR. Integrating adaptive system components and configurations involves incorporating the adaptive components into the higher-level system, which produces the cumulative or synergistic benefits of the components. Integrating an armor system onto an actual vehicle was outside the scope of this dissertation. Instead, an adaptive resilient armor demonstrator was created to show a partial view of how the components would integrate to achieve the adaptive factor states that produce adaptive resilience.

a. Design, Assembly, and Integration

Design of the demonstrator rig began in the previous step. The selection and mapping of components had to occur in a deliberate and targeted manner. The components had to be selected using a precise engineering approach to produce the functional outcome for which they were designed. The design for the demonstrator rig was conducted in a digital fashion. Computer-aided modeling (CAM) was used to create and represent each component in virtual space. Aside from functionality, design of the demonstrator included multiple facets. For example, design elements included fabrication, assembly, reliability, and many other design attributes. Change logs were used to comply with configuration management principles deemed essential to success as the designer modified parts and components of the rig to accommodate assembly and integration.

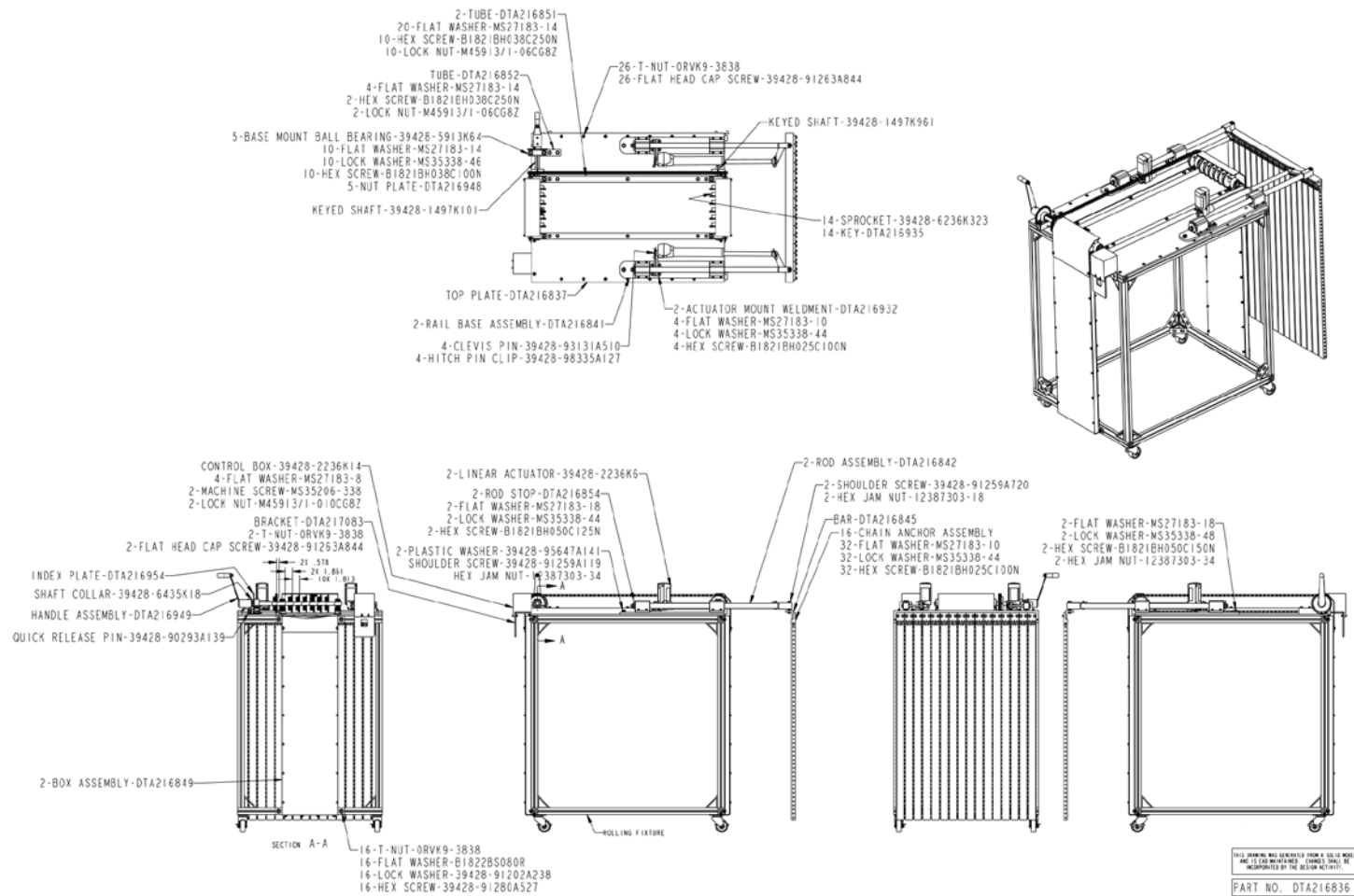
The process of designing the rig began with the representation of the structure or vehicle on which the armor would be placed. Next, the adaptive components were brought together and affixed to the structure to allow their adaptive modes to be leveraged. Affixing of the components was the phase in which the most new parts were created. These parts had to be fashioned and manufactured to enable the mapped adaptive components to perform their functions.



This figure depicts a computer-aided model (CAM) of the adaptive resilient armor demonstrator. Construction of this model in a computer model helps to verify the design and integration feasibility and suitability before the physical fabrication begins.

Figure 75. Digital Computer-Aided Model of the Demonstrator.

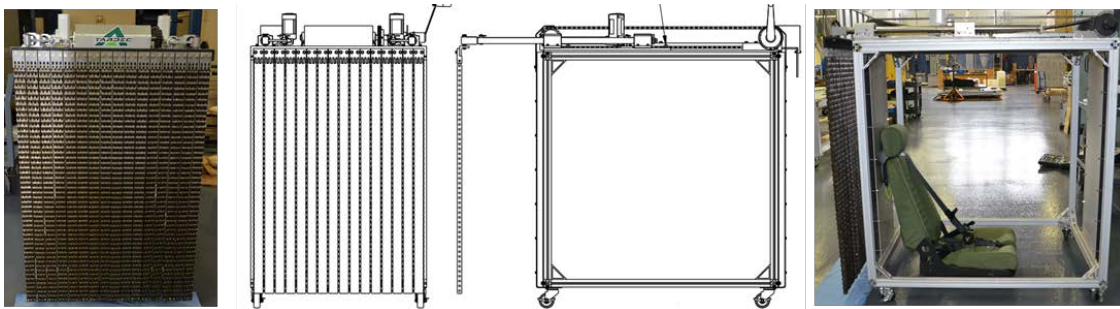
The digital model shown in Figure 75. enabled the system parts and components to be virtually shaped, modified, and verified before being bent, cut, or assembled. Once the digital design was complete, a bill of materials could be created. The parts and components could then be procured or fabricated to begin assembly. The final product of the design was the technical drawing package (TDP). An example page of the TDP appears in Figure 76. The complete TDP for the demonstrator can be found in Appendix A.



This figure shows an image extract from the technical design package (TDP), which serves as a listing of all major component and subassemblies for the adaptive resilient armor demonstrator. The TDP consists of several drawings and assembly instructions for the demonstrator. The complete TDP is listed in Appendix A.

Figure 76. Technical Design of Adaptive Resilience Demonstrator.

When all or most of the components, parts, and hardware were on hand, assembly began. Physical assembly should follow the same flow and process followed in the digital design. In fact, part of the digital design process included designing for assembly. During assembly design, the assembly method should be digitally verified. This is not necessary but serves as an additional way to verify that the components of the system can be properly assembled, allowing the designer to identify interferences and fit issues. Once this phase was complete, the physical verification began. Physically assembling the pieces can be more challenging than digitally assembling the pieces. In the physical assembly process, the tolerances and errors from fabrication can compound and create challenges that must be overcome. In fact, in some instances, parts must be modified or completely redesigned. For example, a weld on one part of the assembly had to be all but removed to allow the pieces to fit properly. This weld was critical to the structural support of the demonstrator rig. The modification and weakness in the structural frame had to be addressed through a redesign. Despite this issue, the physical realization of the demonstrator was a success. This demonstrator was fully functional and achieved all the needed adaptive design configurations it was designed to achieve.



This figure depicts how the adaptive resilient armor demonstrator CAM and TDP were physically assembled into a full prototype demonstrator.

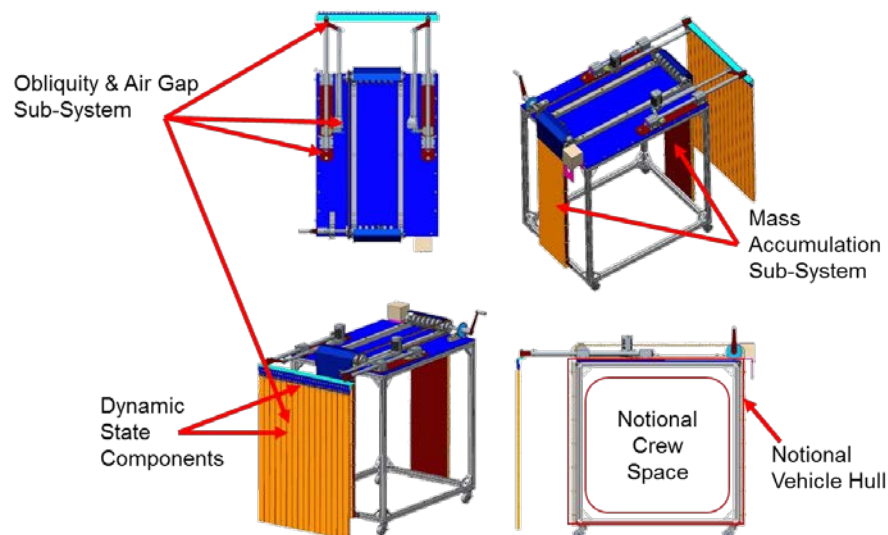
Figure 77. Design to Realization: Adaptive Resilient Armor Demonstrator.

b. Demonstrator Adaptive Design Configurations

The adaptive resilient armor demonstrator successfully combined the mapped components into a fully capable armor system. These mapped components enabled the armor system to adapt to critical design configurations, established by the adaptive factors that

enabled the system to achieve adaptive resilience. The three adaptive factors were armor physical state, mass, and dimensionality.

The adaptive resilient armor demonstrator is shown in Figure 78. This demonstrator represents a portion of a vehicle protected by the adaptive resilient armor. The cube space frame on which the components rest represents the crew and occupant space of the vehicle. Each of the major subsystems on the demonstrator are shown. The dynamic state, obliquity, and air gap subsystems are shown only on one side of the demonstrator because of research resource constraints. The lower right image of the demonstrator rig in Figure 78. should show the external MAAL curtain and actuator system extending from the right side of the demonstrator, not just from the left. However, the mass accumulation subsystem is shown fully on both sides of the demonstrator, with collection bins and drive sprockets on the top of the rig. These subsystems will be described at length in the following paragraphs.

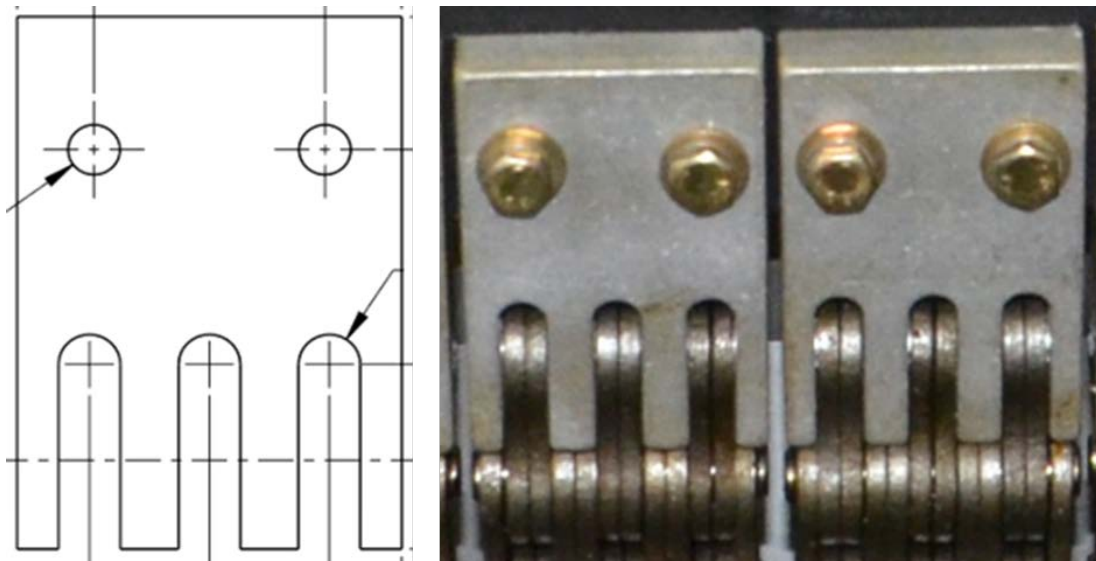


This figure shows the mapped components and where they reside on the adaptive resilient armor demonstrator. The dynamic state, dimensionality and mass subsystems are all represented in the final CAM, TDP and physical prototype of the adaptive resilient armor demonstrator.

Figure 78. Adaptive Resilient Armor Demonstrator and Subsystems.

The dynamic state of the armor was the simplest component to integrate. As mentioned, this component consisted of changing the size and mass of the MAAL strand of the armor system, thereby changing the physical inertial properties of this part of the armor

system. Achieving this adaptive factor consisted of making the MAAL interface adaptor. This component was simple to design, replicate, and scale to the dimensions needed for the MAAL with which it needed to interface. The MAAL strand interface adaptor is shown in Figure 79.

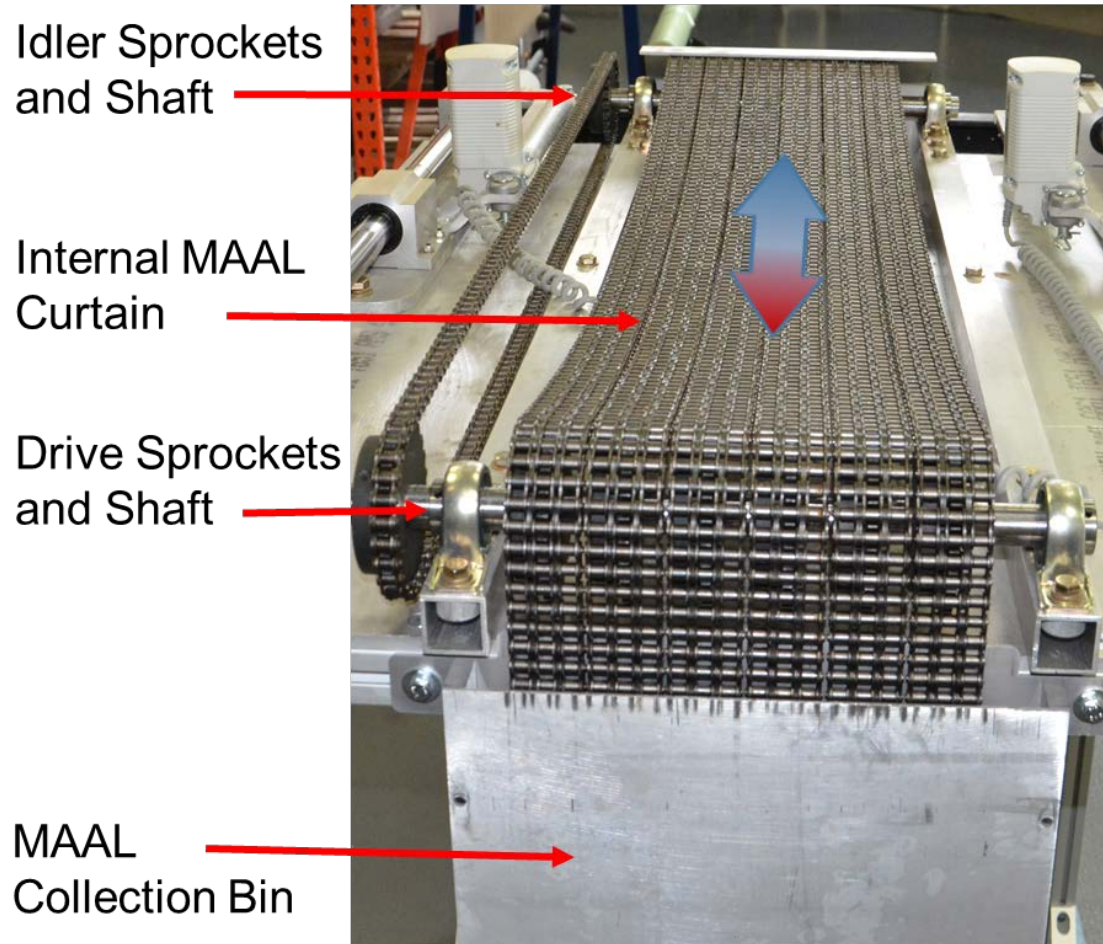


CAD vs. physical prototype MAAL Strand Interface Adaptor.

Figure 79. MAAL Strand Interface Adaptor.

Realizing the mass adaptive factor was a bit more complex. Because this adaptation was an internal reconfiguration, it could be adapted in situ. This process involved moving components and pieces that changed the physical configuration of the system. To achieve the desired adaptive configurations, a subsystem of sprockets, idler wheels, and a collection bin were required to enable the mass of the MAAL strands to collect.

The overall mass accumulation subsystem is depicted in Figure 80. These components enabled the MAAL strand to accumulate, as shown in Figure 81.



The overall Mass Accumulation Subsystem discussed and shown conceptually in Figures 69, 70 and 71 are all physically depicted in this figure. These components enable the MAAL strand to accumulate as shown in Figure 81.

Figure 80. Adaptive Resilient Armor Mass Accumulation Subsystem.

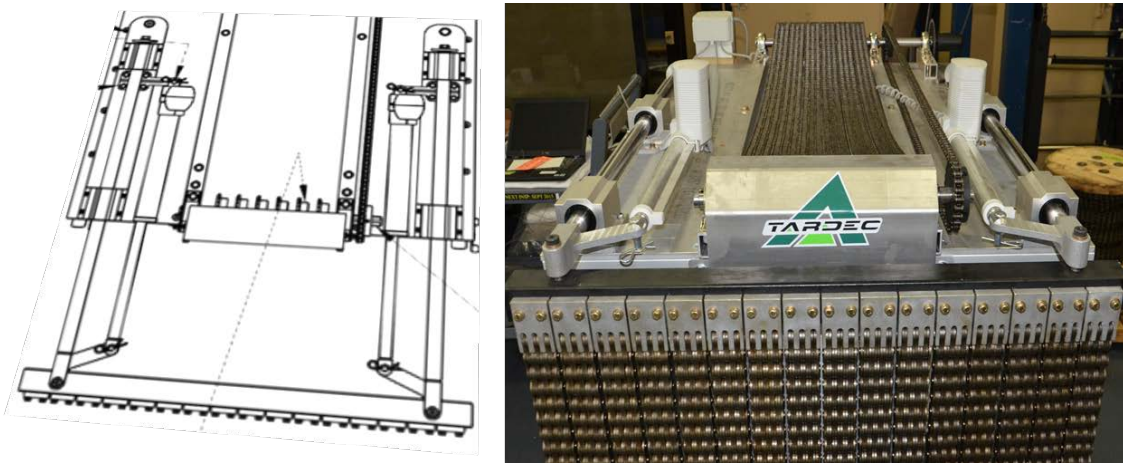


Figure 81. Adaptive Resilient Armor Mass Accumulation Bin.

The mass accumulation subsystem drew MAAL strands from one side of the protected volume to another through reallocation. This accumulation of mass enhanced the ballistic protection where it was needed by reallocating ballistic protection from where it was not needed. Although in the demonstration, the MAAL strand did not stack as pristinely as is shown in the model part of the picture, the MAAL strand did accumulate and stack nonetheless, growing the mass in the trajectory of the threats.

The most complex of the adaptive design configurations to realize were air gap and obliquity. These configurations required a series of actuation, structural, and electronic components that actively moved the ends of the adaptive resilient armor curtain to achieve the enhanced protective states provided by obliquity and standoff.

The subsystem is depicted in Figure 82. The figure shows how the actuator, linear bearing, and other components supported and manipulated the 300 lb. load of the MAAL armor, giving it enhanced ballistic protection through obliquity and air gap. Figures 83 and 84 show how the physical demonstrator adapted to achieve those adaptive configurations. In the middle image of Figure 83, a rule was used to show the range of actuation for the MAAL curtain. The curtain could collapse to a 3" standoff from the vehicle or extend out to a length of 18". The demonstrator was designed to only achieve a 30° angle. However, simple modifications could produce a 60° obliquity if needed.



This figure shows the draft drawings of the obliquity and air gap adaptive dimensionality.
The image on the right shows the physical prototype realization of these component on the Adaptive Resilient Armor Demonstrator.

Figure 82. Adaptive Resilient Obliquity and Air Gap.

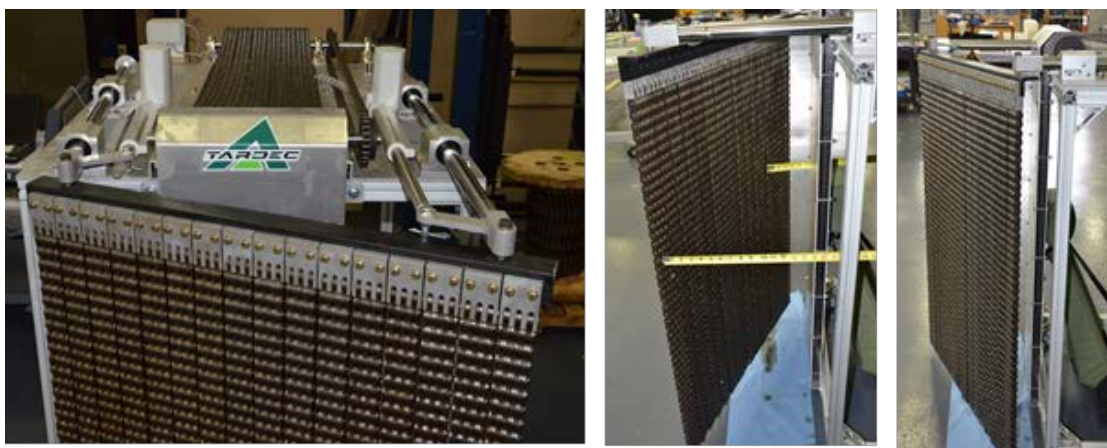


Figure 83. Adaptive Resilient Obliquity.



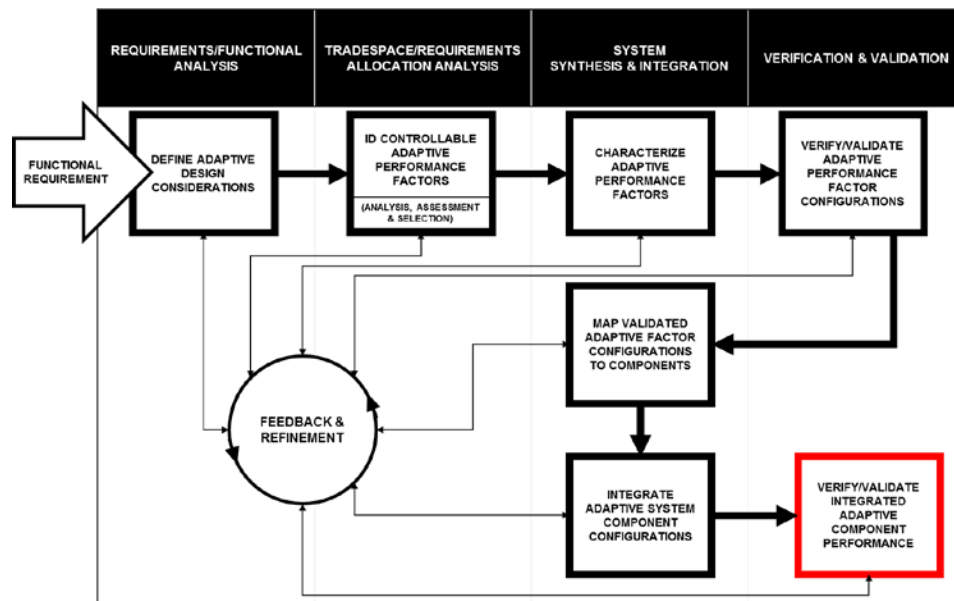
Figures 83 and 84 show how the physical implementations of the adaptive dimensionality components, which create a variable armor air gap and obliquity used to enhance and adapt the terminal ballistic performance of the MAAL armor.

Figure 84. Adaptive Resilient Obliquity and Air Gap.

(4) Summary of Integrating Adaptive System Components

The adaptive resilient armor demonstrator shows the feasibility of the design and adaptive design configurations. The demonstrator was digitally designed and modeled utilizing computer-aided modeling. These models were then used to generate a technical drawing package, which was provided to the machinist and mechanics who fabricated and assembled the parts and adaptive components used to build this adaptive resilient system. The adaptive resilient armor demonstrator possesses integrated means that can achieve the adaptive factor configurations for dynamic state, mass accumulation, and dimensionality, making the whole armor system adaptively resilient.

7. Verify and Validate Integrated Component Performance



Step 7 of the MSIAR seeks to answer several questions. Do all of these components combined realize an adaptive resilient system? Is this the correct adaptive resilient system that will address the originating top-level functional requirement? Furthermore are there any synergistic or parasitic effects from the integration of this adaptive resilient system with itself or as part of a greater system of systems?

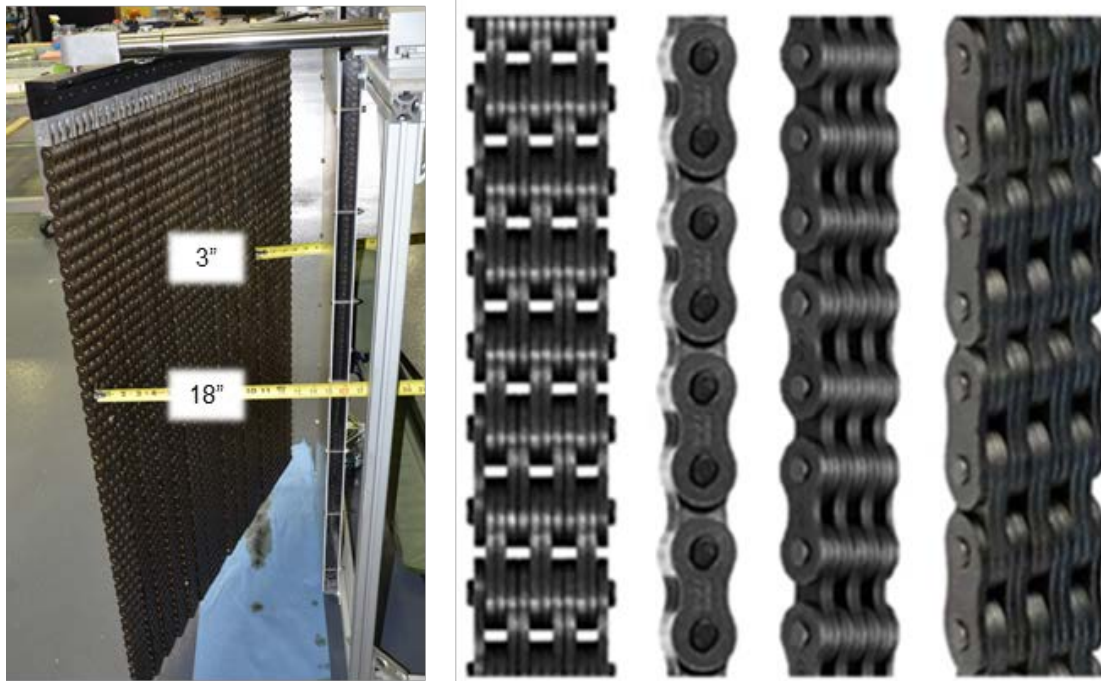
Figure 85. Step 7: Integrate Adaptive System Components and Configurations.

Figure 85. depicts step 7 of the MSIAR. Once the adaptive components are integrated and realized, their performance must be once again verified and validated against the adaptive design considerations that initiated the methodology. The purpose of this step is to

ensure that the physical system components are capable of physically performing at the predicted and functionally required ranges of output. This step helps confirm that the adaptive functions integrated into the subsystems and components physically perform. Verification ensures the integrated components actually achieve the desired system performance and serves to characterize the performance in case synergistic or parasitic effects result from the combinations of adaptive performance factors. Validation ensures that verified integration of components conform to the adaptive design considerations and system functional requirements specified in step 1. Numerous components and subsystems were identified for factorial adaptability; therefore, multiple verifications and validations must occur to assess the suitability of the final system design. As mentioned previously, the potential exists that when combined, these subsystems or components could have negative or counteractive effects on the desired functional output. In combination, they could also have a synergistic effect in which their effect on the desired functional output is positively greater than the sum of their individual performance outputs. The results of combining the adaptive components and subsystems must be compared to the specified functional requirements to ensure they are met or exceeded. If they are not met, then the component(s) are likely not good candidates to achieve adaptive resilience. If this is the case, steps of the methodology must be repeated to identify and create new components. The results of this verification will be shown and discussed in the subsequent proof of concept in Chapter V.

Validation of the integrated components was mostly successful. The adaptive resilience armor demonstrator easily met Adaptive Design Consideration 3. Figure 86. shows the dimensionality adaptive configurations. The adaptive resilient armor demonstrator easily achieved the 3" to 18" air gap allowed for a notional GCV vehicle at 165" (see Figure 41.). However, an obliquity of only 30° can be achieved. Further, the obliquity can only be achieved within the 18" air gap, but not at the 18" air gap. This fact would require a new means to achieve the 60° obliquity and to achieve this obliquity at the fully extended 18" air gap. An alternate way to achieve the desired obliquity ranges would be to rotate the MAAL strands using some mechanism on each strand rather than shifting the full curtain of MAAL strands. This idea is depicted in Figure 86. This would require significant design and engineering because rotating the strands would create vulnerable air gaps between the

MAAL strands. This issue could be addressed through iterating steps 5 and 6 until a suitable solution was found.



This figure shows how the adaptive resilient armor demonstrator's dimensionality adaptive factor configuration was met for the air gap (3" to 18"), but fell short in fully meeting the target adaptive design configuration for obliquity. A better approach may be realized by rotating the individual strands shown on the right side of the figure.

Figure 86. Adaptive Design Consideration 3.

This oversight in the integrated design was mitigated by using the dynamic state and mass adaptive factors configurations that were realized in the final physical design. The adaptive resilient armor demonstrator with the enhanced dynamic state of the MAAL strands achieved ballistic protection against the objective .50-cal APM2 threat at an areal density lower than 20 psf. This ballistic experiment result is shown in the following chapter. This finding validates the fulfillment of Adaptive Design Consideration 1. Adaptive Design Consideration 2 required the system to optimize its design toward the lightest configuration that still met the objective protection requirements. This validation was based on the dichotomous nature of adaptive capacity. Adaptive capacity can be used to exceed the requirement, providing a controlled level of parasitic capacity to counter unknown threats, or it can be used to optimize the system design and meet the requirement at its maximum

factorial design point. Using a 40–2 MAAL strand, at an 18" air gap and 0° obliquity, the MAAL demonstrator provided objective ballistic protection at 16 psf areal density. This was the optimal design configuration with the least areal density at the objective protection level achievable by the adaptive resilient armor demonstrator. Thus, this design fulfilled Adaptive Design Consideration 2. All three adaptive design considerations were validated, which was the final step of the MSIAR. Some design refinements could be made to refine the system, but the design was validated and judged successful against the three adaptive design considerations specified in step 1.

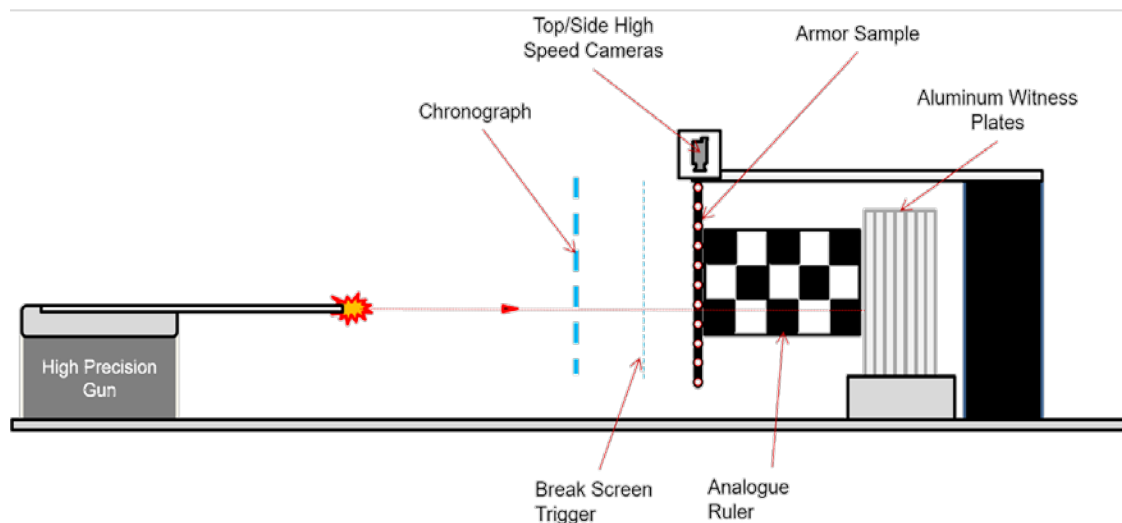
C. SUMMARY OF THE CASE STUDY

The previous chapter introduced an armor technology primer to foster a fundamental familiarization of the concepts associated with terminal ballistics and penetration mechanics. The primer set the stage for the adaptive resilient armor case study to follow. The case study outlined each step of the methodology as it was used to develop an adaptive resilient armor system. The result was the successful realization of an adaptive resilient armor demonstrator, which achieved the adaptive design considerations it was designed to achieve through its adaptive factor configurations. These adaptive design considerations were based on contradictory and challenging user requirements, such as protection, mobility, and transportability. The armor system could expand its ballistic protection levels to exceed its requirement if necessary. When that protection was not needed, the adaptive factor configurations that gave the armor its enhanced ballistic protection could be decomposed to a less implicative state to allow it to meet its mobility or transportability requirements. This is the fundamental benefit of the adaptive resilience attribute. It gives its host system contingency capacity to implement the functions for which it was designed and can be used to bring optimal balance to competing requirements, thus preventing crippling tradeoffs. In the next chapters, the functional performance results of resulting product from this case study will be presented, as well as conceptual views that will further emphasize and support these points.

V. PROOF OF CONCEPT

A. ADAPTIVE RESILIENT ARMOR BALLISTIC EVALUATION

The ballistic characterization of the mechanically adaptive armor linkage (MAAL) armor regarding the adaptive factor configurations was conducted in accordance with standard ballistic test procedures. The ballistic experiments were conducted at the U.S. Army Tank Automotive Research Development and Engineering Center (TARDEC) Ground System Survivability (GSS) Survivability Armor Ballistic Laboratory (SABL). This laboratory is one of the Army's test authorities for the ballistic characterization of armor materials. This facility is an ISO 17025 certified laboratory and is the Department of Defense's authority and primary test center for the automotive tank purchase description (ATPD) 2352 for transparent armors.



The ballistic range setup used for all experiments comprised a high precision gun that fired precisely measured, hand-loaded threat munitions. The threat munitions were fired from the gun, and the threat projectiles passed through a chronograph to measure the projectile's velocity. The projectile then passed through a paper break screen that broke a circuit and initiated the camera to begin filming. The projectile then struck the armor, and the interaction was filmed. An analogue ruler was used to measure residual velocity of the projectile. This data was used to calculate the threat's kinetic energy loss. The disrupted threat then struck a semi-infinite stack of .5" 6061-T651 aluminum plates.

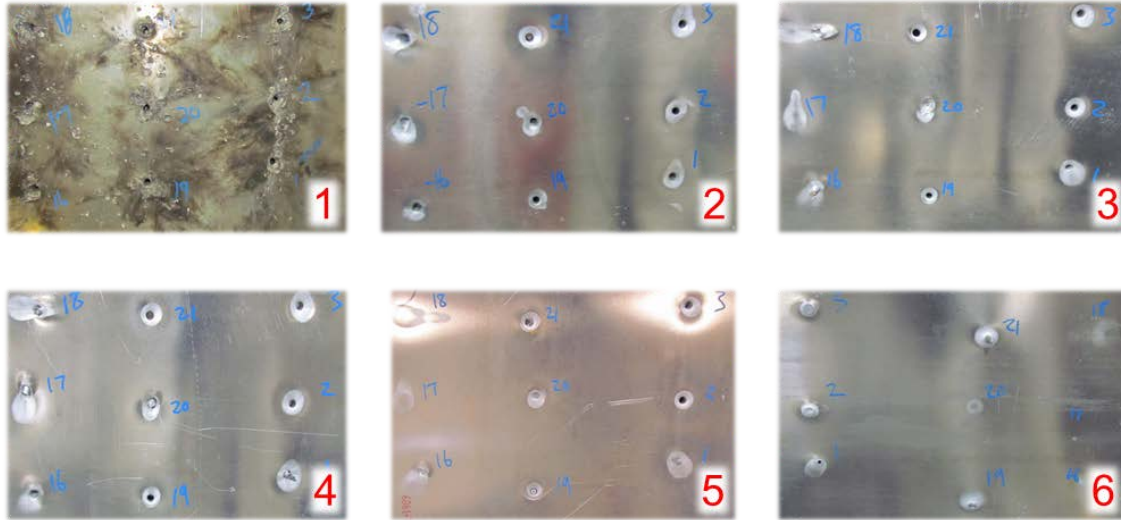
Figure 87. Ballistic Test Range Setup.

The ballistic range setup is shown in Figure 87. The range was fitted with a high-precision gun. This gun was mounted on a 1000-lb. base and had a modular breach that could

accommodate all small, medium, and select large caliber barrels and munitions. The range used a chronograph to capture the ballistic velocity of the fired projectiles. After the chronograph, a break screen was set up, which triggered the top and side high-speed cameras to film the terminal ballistic event. The high-speed cameras were capable of capturing thousands of frames per second. These special cameras were mounted on both the top and side of the target chamber. For this test setup, recording the velocity after the MAAL impact was desired in order to calculate the residual projectile kinetic energy. A standard rule was used to measure the disrupted projectile particle velocities after the MAAL impact.

As previously discussed, the targets for this ballistic characterization were the only nonstandard items. The first target was the MAAL strand. This was the primary adaptive component of the adaptive resilient armor system. This component was manipulated, scaled, and otherwise adapted between each shot. The second target consisted of a semi-infinite series .5" plates of 6061-T651 aluminum. Semi-infinite means that the end or edge effects of the target were designed to have no effect on the ballistic performance. This target setup allowed the MAAL to disrupt the threat projectile, the cameras to witness and record the disruption, the rule to capture the residual velocity, and the softer aluminum to measure the residual penetration of the disrupted projectiles. RHA steel could have been used for the second target but was specifically not chosen because residual penetration would have been far less and more difficult to measure. Further, RHA would not have readily shown the ballistic benefits that the adaptive factor configurations contributed to the ballistic protection of the armor. The softer aluminum facilitated a greater range of residual penetration, making it easier to show the benefits of the adaptations.

During the experiments, the MAAL was placed at the specific point of design interest, and the threat projectile of interest was fired at the series of targets. The projectile struck the MAAL strand, and the residual armor and projectile particles embedded in the aluminum witness plates. A less-protective adaptive design configuration resulted in a residual impact several plates deep, and a more-protective design configuration resulted in a shallow surface impact. The plate in which the most deeply penetrating projectile particle terminated was the plate counted in the total areal density of the target. This is shown in Figure 83.



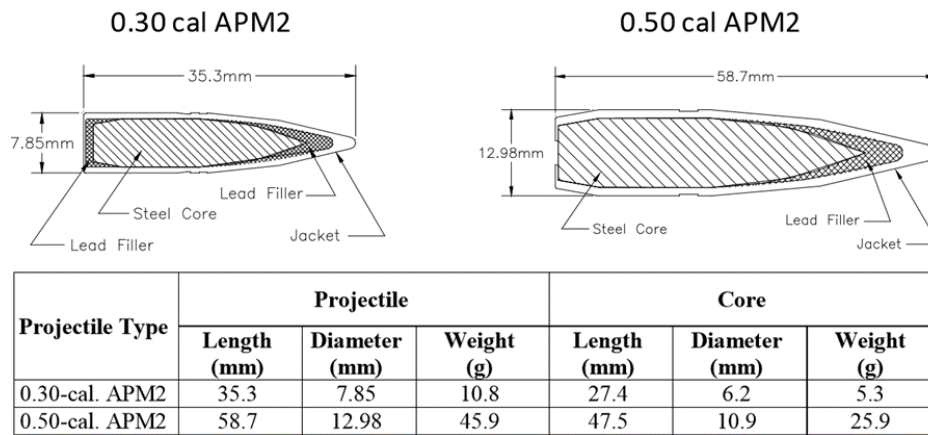
This figure shows an aluminum witness pack from one of the ballistic characterization experiments. The number in the lower right corner depicts the .5-inch aluminum plate order. As shown, the plates have penetration holes. Plates 4, 5 and 6 each show projectile terminations in them. If the projectile terminated in plate 4, the areal density of the MAAL strand plus four aluminum witness plates would be counted in that experiment's terminal areal density. It can be seen across the stack of plates that shot 17 penetrated and terminated in the plate 3 (least), whereas shot 21 penetrated and terminated in plate 6 (most).

Figure 88. 6061 T651 Aluminum Witness Pack.

An impact was regarded as a complete penetration (CP) or failure if the projectile or a resulting target fragment from impact created a hole in the witness plate through which light could be observed after removing the projectile. If an impact did not result in a CP, it was considered a partial penetration (PP), or win. In order to keep residual penetration results consistent, the terminal areal density used this standard.

The U.S. .30-cal. APM2 and 0.50-cal. APM2 were used in this study. These projectiles are shown in Figure 89. The APM2 projectiles have hardened steel cores with hardness of Rockwell C61– 63. These projectiles were used for two reasons. First, a large body of armor characterization results have used these threat projectiles. Second, this was the notional threat used in the MSIAR case study. The first series of experiments were conducted with the .30- cal APM2. After a large battery of experiments, it became evident that the MAAL armor system was potent in terminating these threat projectiles. This was a good result, but unfortunately unhelpful for the purpose of these ballistic experiments. The structure of the catcher phase of the adaptive resilient MAAL armor system was intended to

show how each adaptive factor configuration contributed to the ballistic protection of the armor. The majority of the .30-cal. experiments resulted in splash impacts on the first (front) aluminum plate of the catcher phase. The intention was for these penetrations to occur five or six plates deep and then reduce as the armor system was adapted. The MAAL armor system worked so well that the adaptation configuration effects were indiscernible. After the result, the threat projectile was scaled to .50-cal APM2, which was much better suited for the purpose of these research experiments.



Source: Gallardy (2015).

Figure 89. Dimensional and Mass Characteristics for .30-Cal APM2 and .50-Cal APM2.

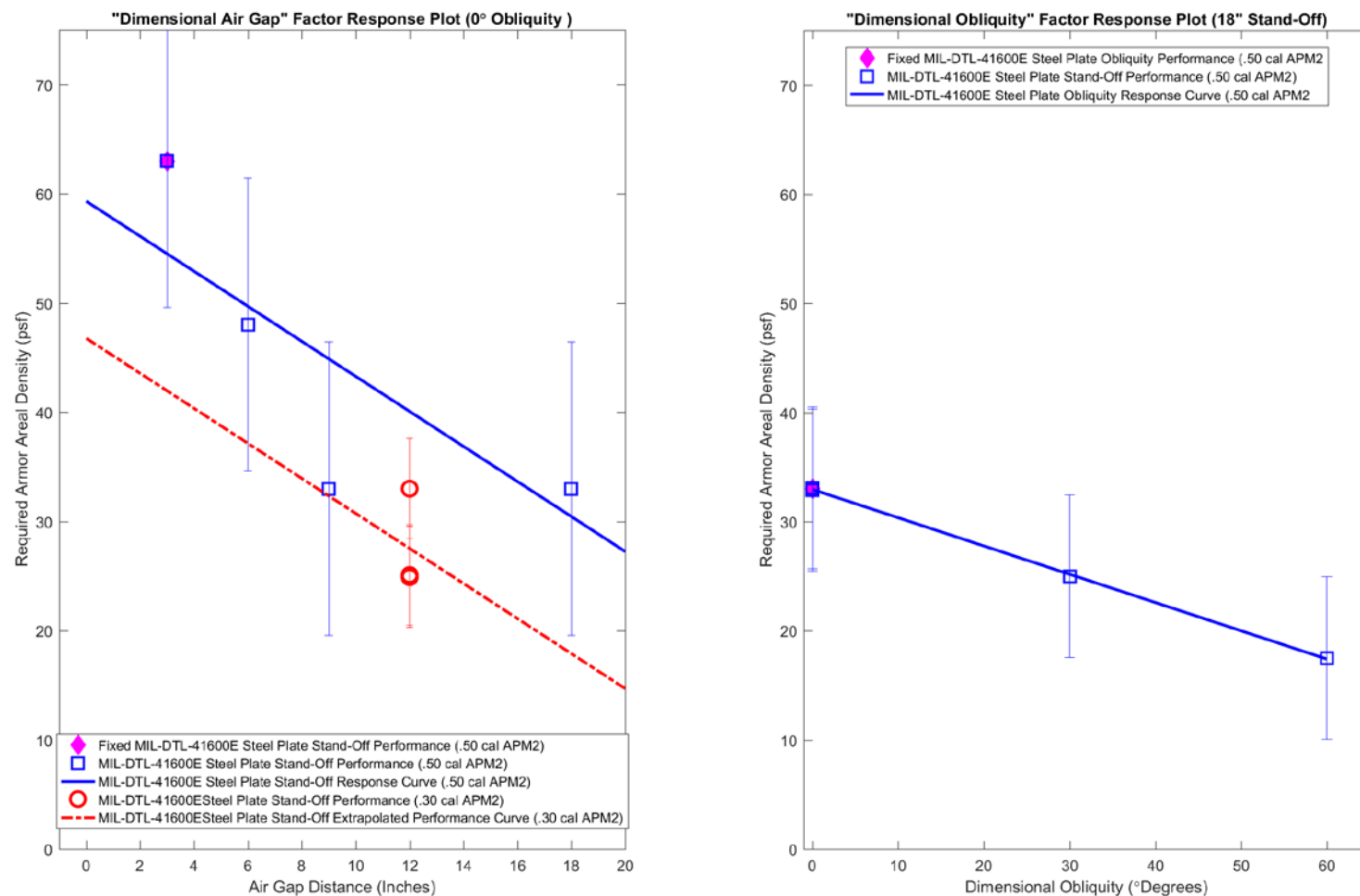
B. ANALYSIS OF RESULTS

The ballistic characterization conducted in support of this dissertation served as an abbreviated form of the two verification and validation steps of the MSIAR. These experiments not only served as the verification and validation steps of the methodology, but also affirmed the efficacy of the methodology in realizing the adaptive resilience attribute in technological systems. The adaptive resilient armor demonstrator and the ballistic characterization served as the proof of concept for this methodology—if followed, significant functional benefit can be achieved. For an armor system, that benefit is realized in an armor system that can terminate threats at lighter areal densities. The ballistic results of these experiments are compared to standard armor steel plate because that is the benchmark against which all ballistic armor is compared. Throughout these plots, a magenta diamond depicts a

similar structured and mass fixed armor design made of MIL-DTL-41600E high hardness steel.

Figure 90. shows ballistic characterization data for the MIL-DTL-41600E high hardness steel. These plots serve two purposes. First, the plots serve as a comparative baseline for the fixed armor plate, which is the foundational armor material most often used in vehicle armors. These fixed plates are fixed and bolted to the exterior of a vehicle and are not capable of being adapted except through a time-consuming external reconfiguration procedure. These plates are denoted by the magenta-colored diamond. There is no trend line associated with these plates—they cannot be readily adapted because they lack adaptive resilience. Figure 90. also shows blue and red plots that do have trend lines associated with them. These plots show the same steel plate, but indicate how it would perform at the adaptive design configurations. These images are meant to show that the MSIAR is unrelated to specific technologies and can be applied to any existing means to obtain more capability. A steel plate armor could be subjected to the MSIAR, and similar adaptive modes and results could be realized. Many of the same adaptive modes used for the MAAL armor could be applied to steel plate, as shown in Figure 90. A steel plate armor system in the same configuration as the one shown can realize adaptive resilient performance.

The plot on the left of Figure 90. shows that a dimensionally adapted MIL-DTL-41600E steel plate can realize up to a 50% reduction in required areal density in terminating a .50-cal APM2. The plot on the right shows that by manipulating the dimensional obliquity, up to another 50% reduction of areal density can be realized. Looking at the magenta diamonds on these plots, a nonadaptive resilient armor with a 3" air gap would require 65 psf armor. At certain adaptive factor configurations, an adaptive resilient armor can achieve that same level of ballistic protection at 15 to 30 psf. To achieve those same areal densities, a nonadaptive resilient armor of the same structure would require an 18" standoff from the side of the vehicle. This would then implicate the transportability and mobility of the platform, adding 3 feet to its overall length and width. This is a simplistic example, but it captures the essence of the adaptive resilience attribute's enhanced capability while simultaneously mitigating the requirement's tradespace.

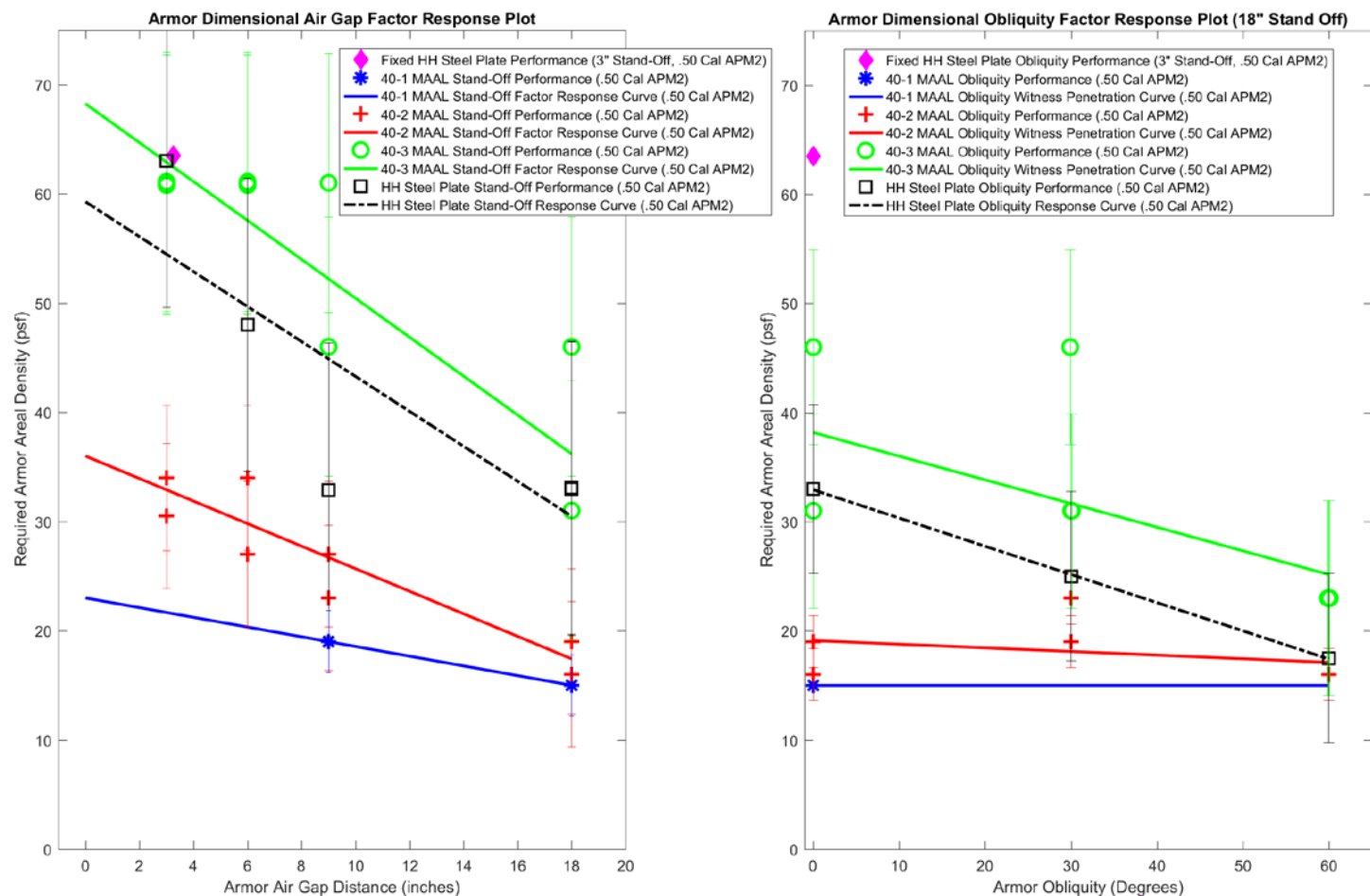


These plots depict the baseline experiments of high hardness steel at adaptive factor configurations. These are meant to serve as a baseline to compare the MAAL armor characterization plots. They are also meant to show that MAAL armor is not necessarily needed to achieve the adaptive factor configurations and that steel plate can be used to achieve many of the same adaptations that the MAAL enables.

Figure 90. MIL-DTL-41600E Steel Plate Ballistic Characterization Plots.

Figure 91. depicts the ballistic characterization results for 40–1, 40–2, and 40–3 MAAL armor at desired adaptive factor configurations for dimensionality. In addition, these plots portray the difference in performance between these three MAAL strand widths. The 40–3 MAAL strand is essentially three 40–1 strands affixed side by side. This gives each strand a different mass and therefore inertial dynamic state; however, the areal density for the two strand widths remains the same. It is readily evident that an adaptive resilient armor using any of the three widths of size 40 MAAL provides more capability than a nonadaptive resilient fixed steel plate armor.

Figure 91. shows both the air gap and obliquity dimensionality adaptive factors. The air gap dimensionality response line shows significant increase in performance for all three sizes of MAAL. Obliquity shows a smaller increase in performance but an increase nonetheless. The 40–2 and 40–1 MAAL obliquity response lines show very little increase. This is likely because of the narrower widths of the strands. However, it is clear that the 40–2 and 40–1 MAAL strand far outperform the 40–3 MAAL strand in required terminal areal density. It is also clear that the adaptive resilient armor designs provide more ballistic protection at reduced areal density than the similar static RHA design. The adaptive resilient armor scales its protection level when needed to meet or exceed its ballistic protection requirements through these dimensional adaptations, and then collapses its dimensionality when this high performance state is not needed. This adaptive resilient dimensionality provides the armor system enhanced top-level performance without any parasitic capacity to the detriment of the host platform's transportability or mobility.

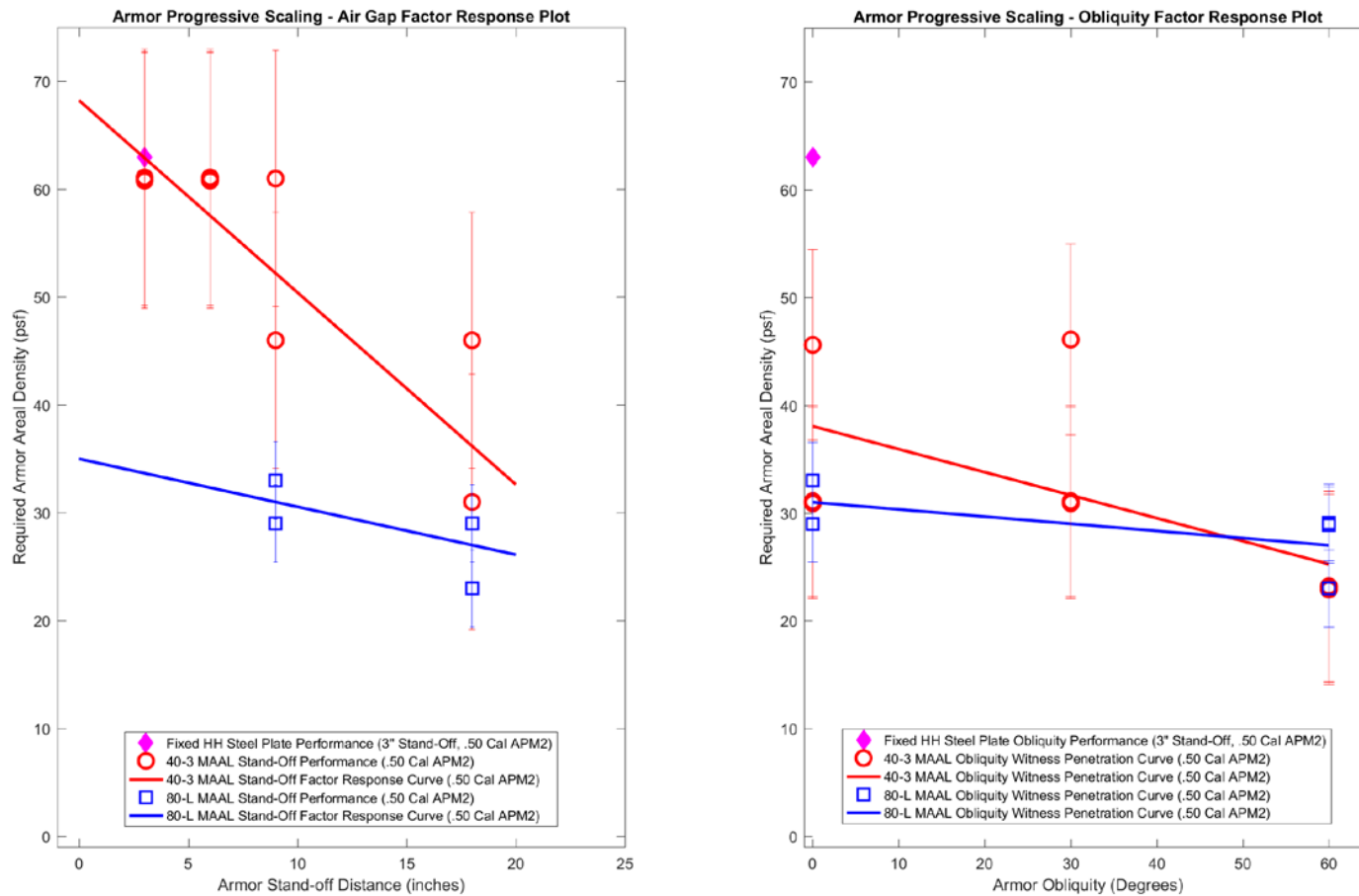


These plots depict the core proof of concept ballistic experiments for the MAAL armor at key Adaptive Factor Configurations. The plots primarily show the performance at key dimensionality adaptive factor configurations. It should also be noted that both plots show variable strand widths of size 40 MAAL. The 40–3 (triple strand) performed poorly compared to the high hard steel plates 40–2 and 40–1. This indicates that the inertial state of the lighter and narrower strands offer better ballistic disruption.

Figure 91. 40-1, 40-2, 40-3 MAAL Ballistic Characterization Plots.

Further, this adaptive dimensionality can provide this enhanced protective capability in a matter of moments. These adaptations are internal reconfigurations. The adaptive resilient armor demonstrator was capable of achieving every adaptive factor configuration shown in Figure 91. in less than 30 seconds. This is unprecedented—in situ obliquity and air gap adaptations, even in external reconfiguration adaptive modes, were considered too time consuming and generally burdensome to be of value. These dimensionality adaptations can be used predictively to achieve a T1R system state. If a threat was known or expected to come from a certain direction, the air gap and obliquity could be optimally adapted to protect from that direction of attack. These dimensionality adaptations could also reactively achieve a T2R system state. If a threat was penetrating a platform, the air gap and obliquity could be used to recover the protected functional state (to a point) by adapting itself to an adaptive factor configuration that would enable the armor system to regain its protection.

Figure 92. depicts mass and dynamic state adaptive factors and how they can be adapted through external reconfiguration and progressive scaling. As mentioned previously, external reconfiguration is an adaptive mode in which external means (e.g., mechanisms, processes, and artifacts) produce functional system resilience. Progressive scaling occurs when the adaptive capacity is expanded via external means. In this instance, a thicker and heavier MAAL effector strand (size 80) replaced a lighter and thinner MAAL effector strand (size 40). The ballistic characterization plots show that the size-80 MAAL strand defeated the .50-cal APM2 at a lighter overall areal density for both the air gap and obliquity adaptive configurations. At its baseline experimental adaptive configuration (3" air gap and 0°) the size-80 MAAL terminated the threat at almost 50% less areal density than did the size 40. This finding indicates that the size 40 possesses less ballistic protection capability. This is true; however, it is not less capable in its adaptive resilient protective capability for this threat. Note the differing response plot slopes. The size-40 chain has a steeper slope than does the size 80. This means that greater adaptive performance was achieved by the size 40 for this threat.



These plots depict an example of the external reconfiguration known as progressive scaling. Progressive scaling replaces an existing system component with another component of greater capacity. In this instance a size-40 MAAL strand ballistic protection performance is compared with a size-80 MAAL strand ballistic protection performance. The size 80 outperformed the size 40 in required areal density but did so with the penalty of unused parasitic capacity. This is evident in the less steep response slope of the size-80 MAAL, compared to the slope of the size-40 MAAL. This result is shown in both plots.

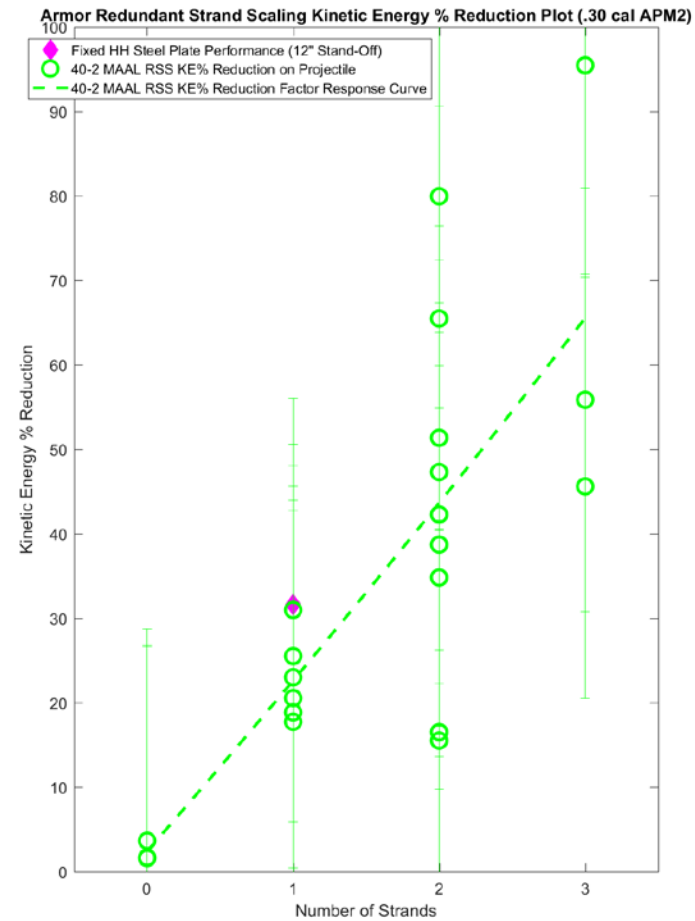
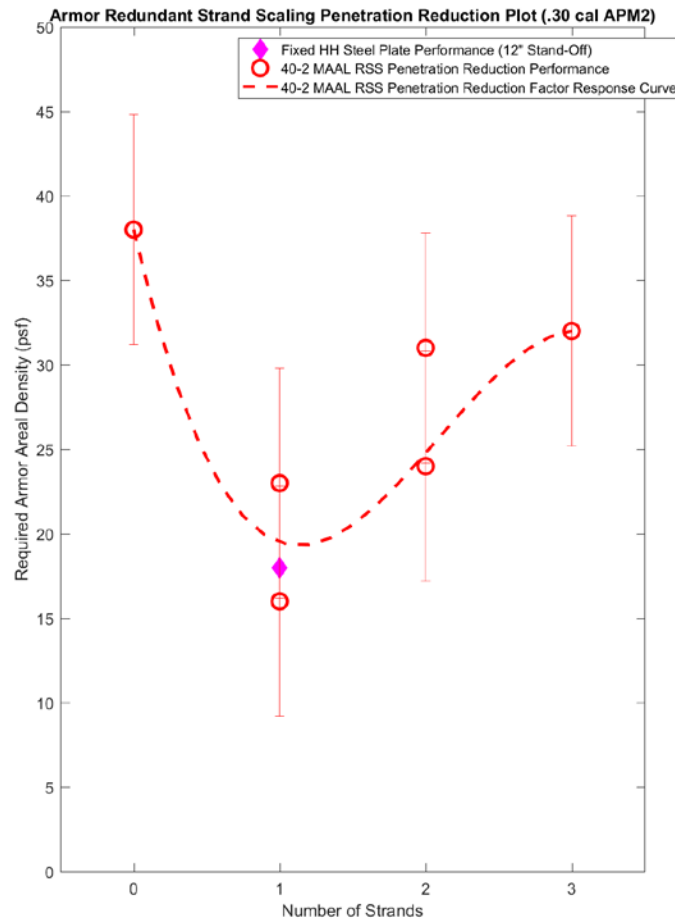
Figure 92. Progressive Scaling Adaptive Factor Characterization.

The size-80 MAAL likely greatly overmatched the threat. This strand created parasitic protection capacity against the .50-cal threat. This result may or may not be acceptable, depending on the operational environment. The MAAL adaptive resilient armor system will likely be placed on a vehicle platform with a fixed-base armor. The adaptive part of the MAAL armor system is the MAAL effector strand. This means that the MAAL catcher plates would be a fixed material solution or base armor on a vehicle. If the size-80 MAAL strand was over performing against the threat, the catcher base armor would be underutilized and therefore considered parasitic capacity. In short, the size 80 can terminate the threat at a lighter areal density but with parasitic capacity unused. If the threat were scaled to a greater penetrating threat, the size-80 MAAL strand would likely have a steeper response plot slope, thus offering greater adaptive resilient protective capability with less parasitic capacity. This adaptation would likely be useful when an enemy force scaled the threat class it used against the platform. This external reconfiguration adaptation is enabled by the MAAL strand interface adaptor. Swapping out these MAAL strands can occur in a matter of minutes with commonly available tools. Referring back to the resilience basins shown in Figure 13. of Chapter II, the plots shown in Figure 92. represent how the adaptive basins can nest within each other. The size-40 MAAL strand represents the smaller basin with its adaptive configurations, nested within the larger basin, represented by the size-80 MAAL strand. This stacking of scalability is a key principle in the adaptive resilience attribute. The greater the number of nested basins or degrees of adaptability in a system, the more adaptive resilience it possesses.

Figure 93. depicts the redundant strand scaling characterization plots. These experiments progressively added MAAL strands to the adaptive resilient armor system to show an increase in ballistic protection capacity achieved by this external reconfiguration adaptation. These experiments are among the first to be conducted with .30-cal APM2. The results showed that the MAAL armor system significantly overmatched the .30-cal APM2; the residual impact on the catcher portion of the system typically terminated in the very first plate. This made measuring the effectiveness of this adaptation difficult. Fortunately, kinetic energy reduction measurements were also taken. The plot on the left shows that the total areal density increased, as would be expected when adding additional MAAL strands to the armor

system. The plot on the right shows the percentage of kinetic energy reduction achieved by adding each additional MAAL strand. Although kinetic energy reduction cannot be translated into terminal areal density, the result definitely implies that the penetration potential was dramatically reduced for each strand added. The plot on the right shows approximately a 50% mean reduction in kinetic energy for each MAAL strand added. This implies that the external reconfiguration of redundant strand scaling potentially had a dramatic effect on the terminal areal density of this adaptive resilient armor system.

These ballistic characterization plots show the efficacy and value that an adaptive resilient armor can have over a nonadaptive resilient armor. The added enhanced ballistic protection capacity and operational flexibility provided by an adaptive resilient armor would be of great benefit in a complex operating environment in which the threats and operating conditions are constantly in flux. The data in these plots quantitatively show the benefits of this system, but still only in a numerical fashion. The following paragraphs will provide visual context to adaptations of this adaptive resilient armor system and other adaptations not experimentally validated for an adaptive resilient armor on a notional combat vehicle.



These plots depict an example of the external reconfiguration known as redundant scaling. Redundant scaling supplements an existing system component with additional component of the same capacity. These experiments were conducted with .30 cal APM2. This threat projectile was overmatched by the ballistic mechanics of the MAAL strands. Little data could be collected from the residual penetration after the MAAL strand impacts because most terminated in the first aluminum witness plate. What can be seen is the percentage of kinetic energy reduction each strand contributed to the ballistic performance of the adaptive resilient armor system.

Figure 93. Redundant Scaling Adaptive Factor Characterization.

C. ADAPTIVE RESILIENT ARMOR SYSTEM

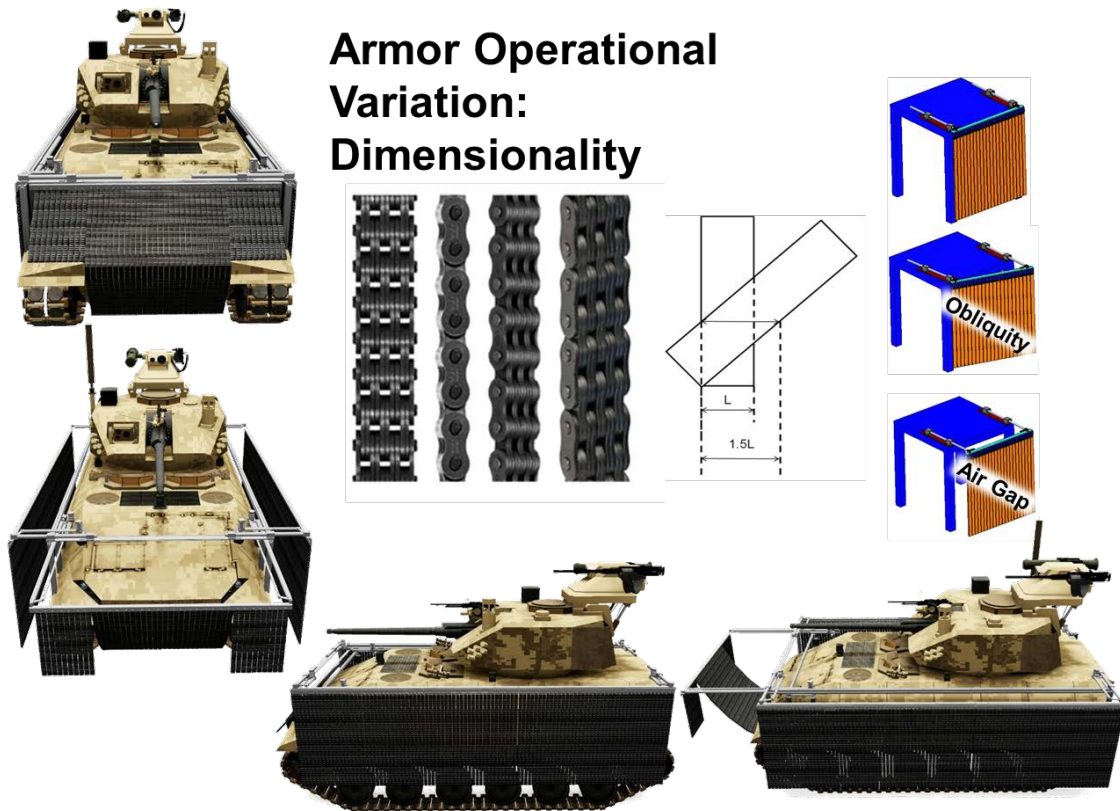
Chapters III and IV provided discussions of complicated subjects in a qualitative and quantitative fashion. Armor technology, ballistic protection data, and systems engineering concepts were combined to achieve superior system performance. These discussions are helpful for those who are conversant in these fields, but likely meaningless to those who are not. The following paragraphs will describe with visual detail how an adaptive resilient armor system on vehicles may actually function.

In Chapter II, T1R and T2R were described as beneficial system attributes. These attributes of resilience are usually limited in their ability to be realized in technological systems because adaptive capacity to realize these attributes was inappropriately addressed during system design and engineering. Adaptive capacity is provided through the two modes of adaptation: external and internal reconfiguration. Internal reconfigurations are system adaptations that utilize means (e.g., processes, mechanisms, and artifacts) within the system to achieve desired functionality. External reconfigurations are system adaptations that involve external means to achieve desired system functionality. Internal reconfiguration includes adaptive means that were present within the system at the time of the functional disturbance or incident. Adaptive Mode 2 involves external means (e.g., mechanisms, processes, and artifacts) that were not present in the system when it lost its functionality but when applied after the fact, enable the system to regain its functionality. Internal reconfiguration can occur four ways: operational variation, reallocation, degeneracy, and exaptation. The following paragraphs show how internal and external reconfigurations can be realized on an armor system to produce a desired state of adaptive resilience and enhanced ballistic performance described in the previous sections.

1. Adaptive Resilient Internal Reconfiguration

Operational variation was the most responsive of the adaptations used to achieve adaptive resilient ballistic protection. This was shown in many of the ballistic characterization plots in the previous section. The adaptive resilient armor employed the adaptive factor of dimensionality. By adapting dimensional air gap and obliquity, significant adaptive capacity can be leveraged to produce a range of ballistic protection with minimal

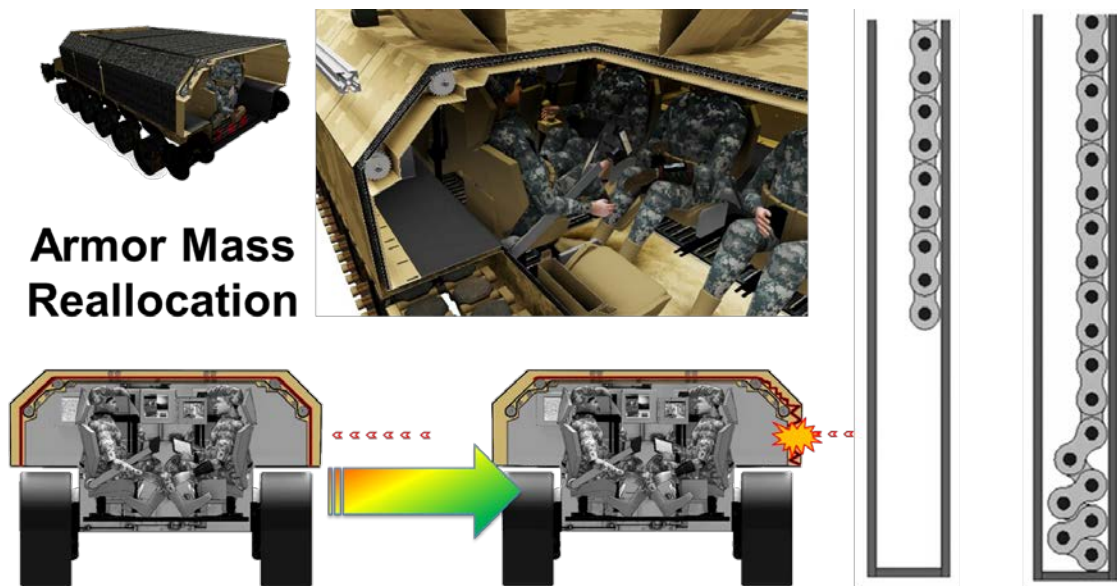
tradeoffs to competing requirements. Figure 94. shows how this adaptive means could be realized on a combat vehicle. As discussed in Chapter IV, the adaptive components mapped from verified adaptive design configurations are visually realized on the notional combat vehicle. The depictions in this figure show a MAAL armor system that can be adapted through enabling components to provide a dimensional shield around the vehicle. These components are capable of adapting the air gap and dimensionality through internal reconfiguration to provide added capacity to the ballistic protection of the combat vehicle system with minimal parasitic capacity. The efficacy of this adaptation was shown in Figure 93.



This figure shows a conceptual implementation of the MAAL armor and how it could be adaptively implemented on a combat vehicle. The images show examples of how air gap and obliquity can be manipulated to achieve the adaptive performance factors associated with armor dimensionality.

Figure 94. Adaptive Resilient Armor: Operational Variation.

Internal reconfiguration can also be realized through the adaptive armor mass reallocation. Figure 95. shows an internal MAAL armor system within the walls of the combat vehicle system. This internal MAAL system internally drapes over the inner walls of the combat vehicle. This curtain of MAAL connects to a drive-sprocket system that pulls the curtain of MAAL from one side of the combat vehicle to the other depending on the location of the need for additional ballistic protection. Figure 95. shows how this mass reallocation would occur, accumulating the reallocated MAAL mass into the side of the vehicle where added capacity is needed. It has been shown that increasing the trajectorial mass of an armor increases its ballistic protection.



This figure shows a conceptual implementation of the MAAL armor and how it could be adaptively implemented to adaptively reallocate armor on a combat vehicle. A MAAL curtain could reside within the hull walls of the combat vehicle. This curtain could be manipulated with sprocket drive system that would enable the MAAL armor to accumulate over areas of the combat vehicle where added protection is required.

Figure 95. Adaptive Resilient Armor: Reallocation.

Exaptation is an adaptation through which existing means are employed in novel ways in response to new environments and challenges. The MAAL strand was shown to have significant utility in armor systems. However, what if there were other ways these artifacts could be used to enhance their host system's survivability? Figure 96. depicts the

survivability framework known as the ground-system survivability onion. Each layer or peel of the onion represents a functional mode that enhances the survivability of a platform. The framework starts with the threat point of origin at the outside of the platform and moves in toward the vehicle platform. Actions or capabilities that perform the function at each layer contribute the cumulative whole of the system's survivability. This framework can be formulaically shown in Equation 7.

$$P_{SURV} = 1 - ((P_{DET})(P_{HIT/DET})(P_{KILL/HIT}))$$

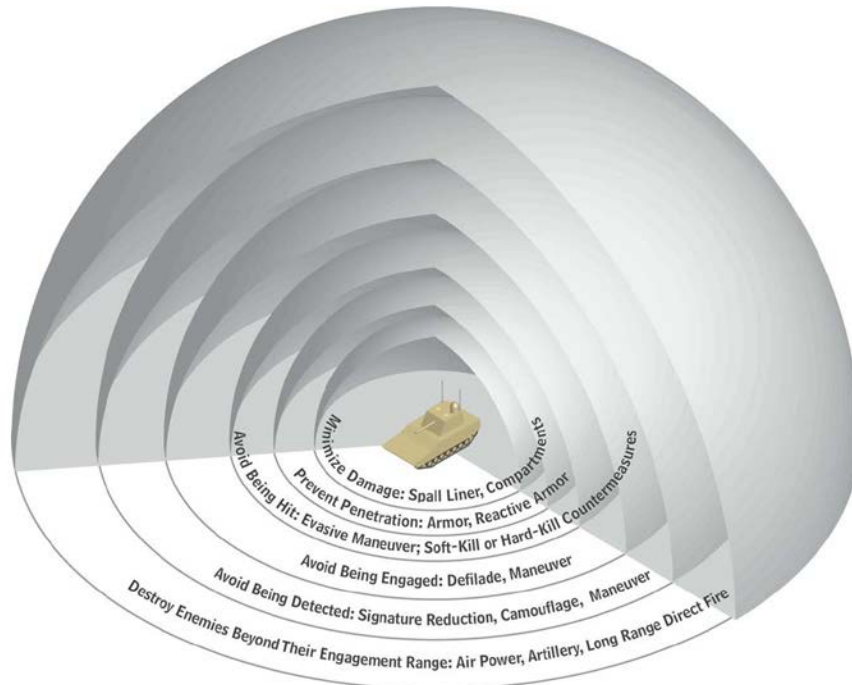
where :

$$P_{SURV} = \text{Probability of Survivability}$$

$$P_{DET} = \text{Probability of Detection}$$

$$P_{HIT/DET} = \text{Probability of Hit if Detected}$$

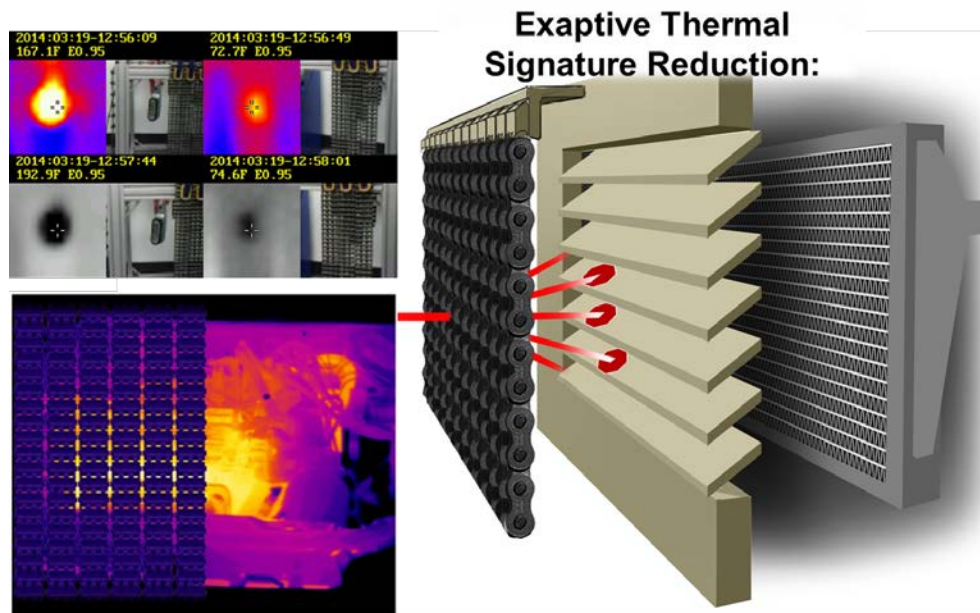
$$P_{KILL/HIT} = \text{Probability of Kill if Hit}$$
(7)



The survivability onion is a common framework to understand ground-system survivability. This framework works from the threat inward toward the vehicle. Other frameworks work from the vehicle outward toward the threat. Armor systems typically contribute to the last two shells of the onion: penetration prevention and damage mitigation. Are there ways an armor could contribute to other shells of the survivability onion? Source: Kempinski and Murphy (2012).

Figure 96. Survivability Onion.

Figure 97. depicts an exaptive use of the MAAL armor strand, which contributes to the host system survivability by enhancing its ability to avoid being detected. Thermal signature is critical survivability, given the prevalence of thermal target acquisition systems on the battle field. MAAL strands have proven to have a unique capability to not only provide ballistic protection, but also to do so in a manner that can obscure thermal gradient on the vehicle hull behind the strand. This trait gives MAAL armor added survivability capability over traditional armors and makes it a suitable candidate for use in exhaust ports and radiator grills on vehicles. These are traditionally known to be vulnerable locations because by nature, they have a direct unprotected path to critical system components. Additionally, they project a highly detectable thermal signature. Traditional armors typically heat up around these ports. In contrast, MAAL strands' air gaps allow the heat to flow and convect more easily to the environment without heating the MAAL strand material that would otherwise project detectable infrared radiation observable to threats. Further, the adaptive resilient dimensionality discussed previously also adaptively enhances this thermal signature mitigation effect. The closer the strand is to the heat source, the less mitigation of the signature. The further in front of the heat source, the better the thermal signature is obscured. The efficacy of this adaptation is shown in the upper left image of Figure 97. Here the thermal gradient is greatly reduced by the MAAL strand.

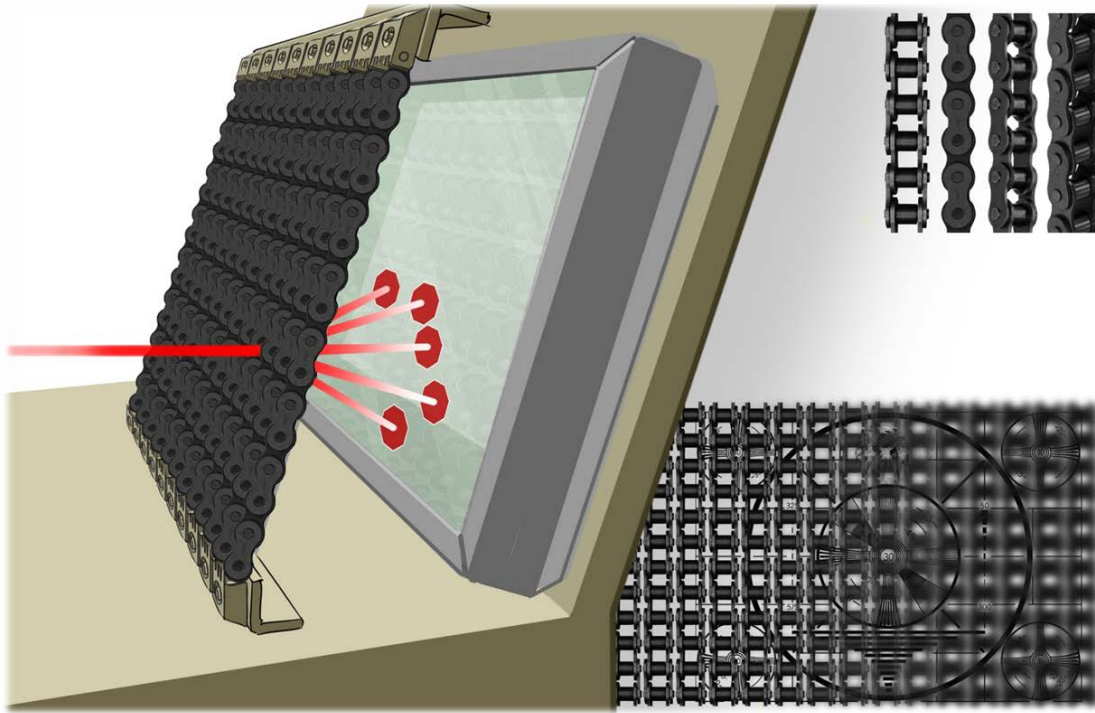


MAAL strands can be employed in an exaptive fashion to mitigate the thermal signature of a platform and its high infrared radiation areas. The image on the upper left shows a blow dryer in a nonshielded configuration and a MAAL shielded configuration. The nonshielded configuration gives off a highly visible thermal signature detected at 167.1° Fahrenheit. The MAAL-shielded configuration projects a much less detectable thermal signature, at 72.7° Fahrenheit.

Figure 97. Adaptive Resilient Thermal Signature Management: Exaptation.

Degeneracy is a mode of adaption in which an artifact can serve as the means to conduct a prescribed function but is more appropriately qualified to accomplish other functions. Certain types of MAAL strands are transparent. This quality makes them potentially usable as a transparent armor. However, the MAAL strand may not be the most suitable transparent armor, because the strand is meant to be frangible, fragmenting in a ballistic event. If a ballistic glass window on a vehicle were damaged, and this viewport was mission critical to the function of the system, replacing that ballistic window with a MAAL strand could provide a degenerate-level transparent protection from thrown objects and some ballistic threats. The ballistic window is the ideal solution; however, a MAAL strand could serve, in a degenerate fashion, the same purpose, as shown in Figure 98.

Degenerative Transparent Armor

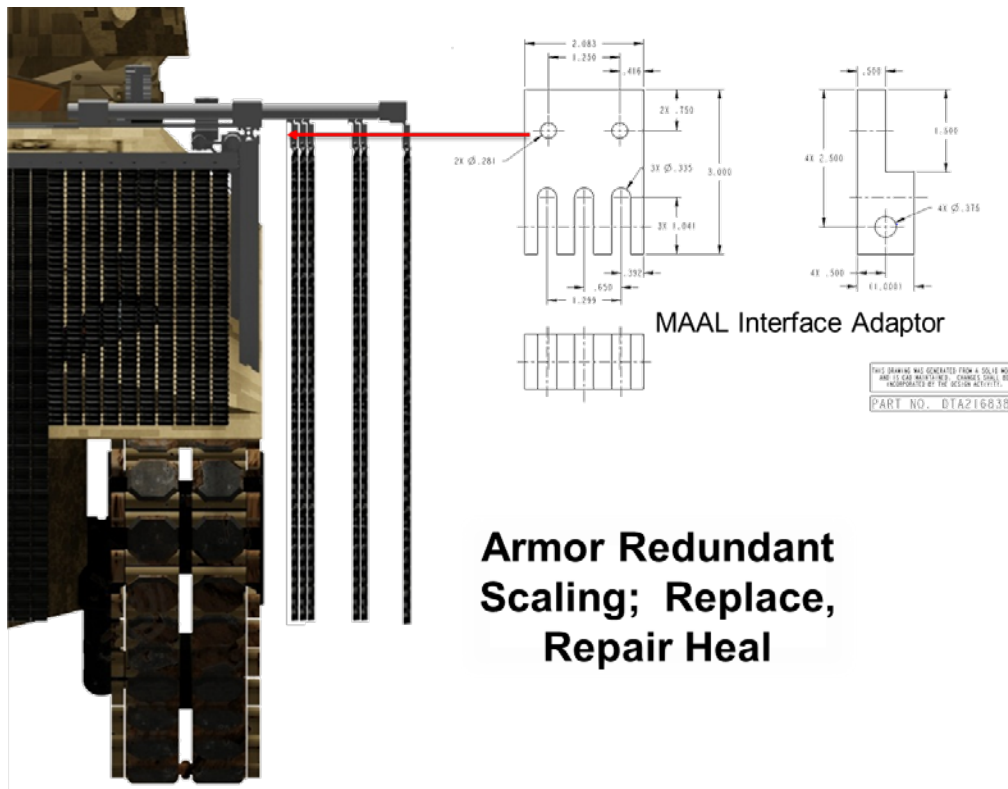


MAAL strands can serve as a viewport. Although not ideal for a transparent armor, in certain circumstances or configurations, as shown in the operation view image on the left, the strands could serve or enhance the ballistic performance of a transparent armor.

Figure 98. Adaptive Resilient Transparent Armor: Degeneration.

2. Adaptive Resilient External Reconfiguration

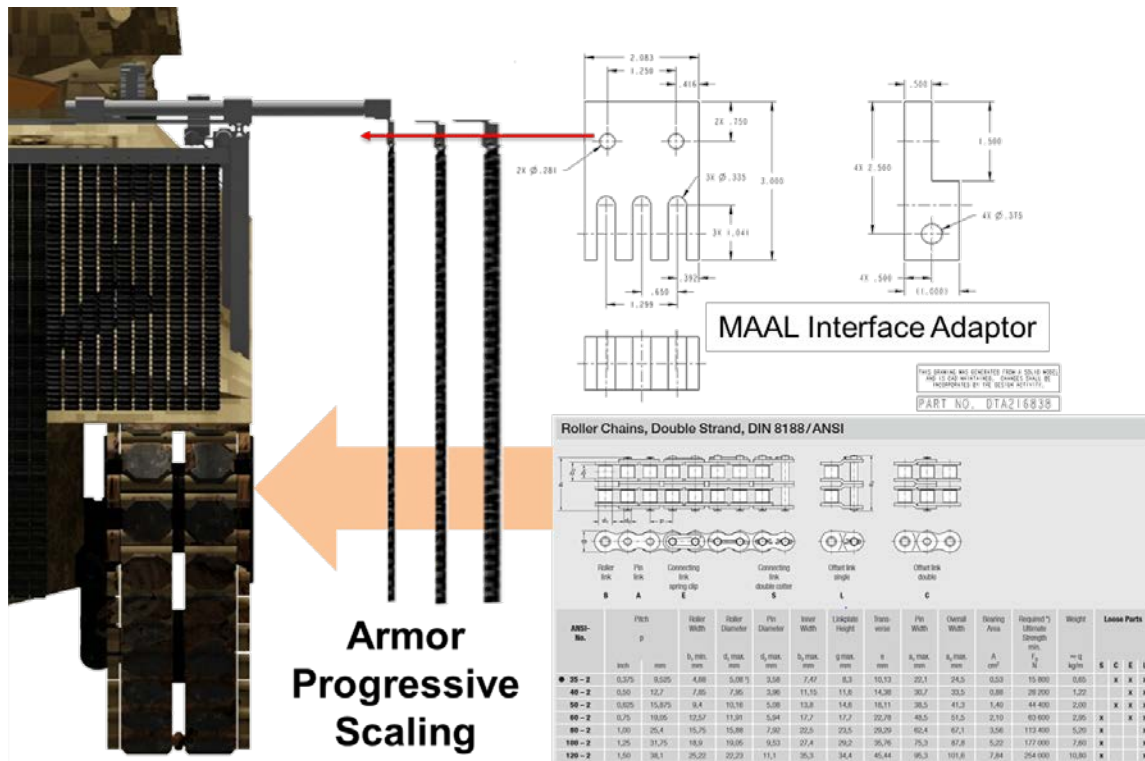
External reconfigurations can occur through three ways: redundant scaling; progressive scaling; and replacement, repair, or healing. Redundant scaling is a form of external adaptation in which the means to overcome a disturbance are appropriate but insufficient or lacking the amount of resources needed to overcome the disturbance. Figure 99. shows how an adaptive resilient MAAL armor system could employ redundant scaling to increase the ballistic protection of a vehicle. This adaptation simply multiplies the number of strands in the trajectory of the threat projectile. The MAAL interface adaptor makes adding additional strands in a redundant fashion quick and simple, adding to the adaptive resilience of the system. The efficacy of this adaptation was shown quantitatively in Figure 93.



Redundant scaling of an adaptive resilient MAAL armor consists of adding additional strands of the same size to the effector phase of the MAAL armor system. This adaptation is enabled by the MAAL interface adaptor, which allows the additional strands to be quickly added when needed.

Figure 99. Adaptive Resilient Armor: Redundant Scaling.

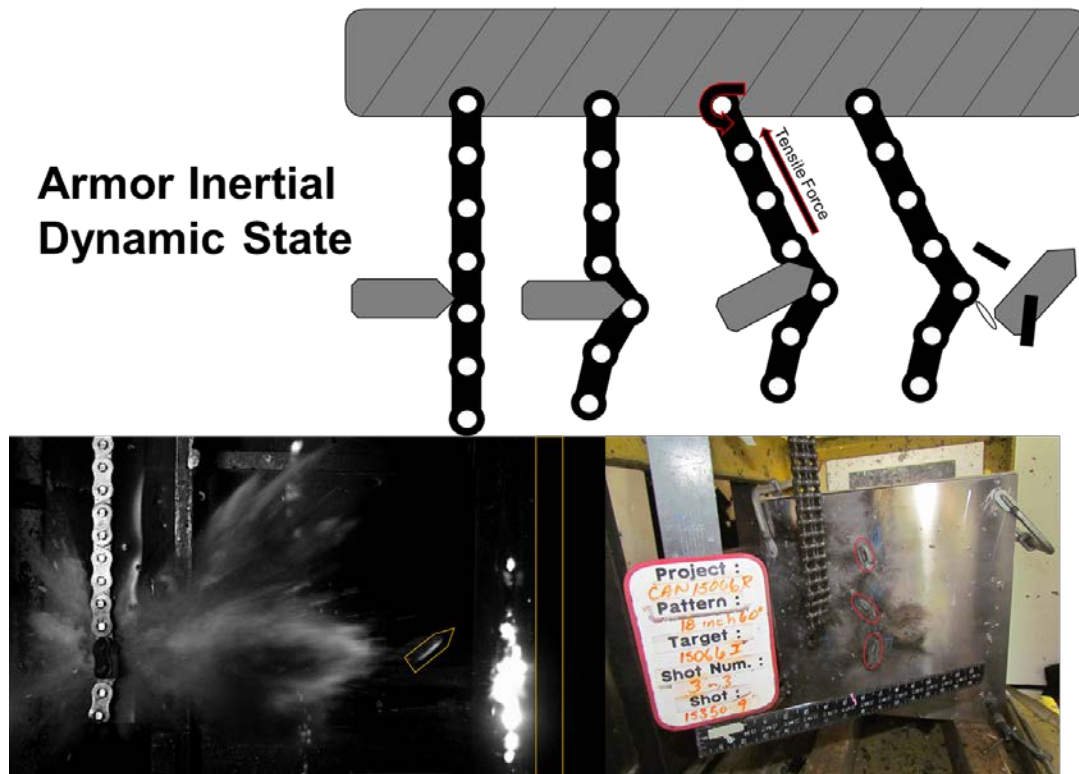
Progressive scaling is similar to redundant scaling in the sense that the original system lacks the magnitude of means to accomplish a task. However, it differs in the sense that instead of duplicating the means to accomplish the function, a single means of greater magnitude is applied. Figure 100. shows one of two ways to employ progressive scaling adaptively. If mass of the MAAL strand is of minimal concern, simply adding a heavier strand of MAAL will provide added protection, especially in instances in which a heavier than expected threat is encountered and ballistic protection must be scaled. The MAAL interface adaptor enables quick external reconfigurations. The efficacy of this adaptation was shown quantitatively in Figure 92.



Mass progressive scaling of an adaptive resilient MAAL armor consists of adding strands of increased size and mass to the effector phase of the MAAL armor system. This adaptation is also enabled by the MAAL interface adaptor, which allows the heavier strands to be quickly added when needed.

Figure 100. Adaptive Resilient Armor: Mass Progressive Scaling.

Inertial progressive scaling of an adaptive resilient MAAL armor is a bit more refined, compared to the mass progressive scaling. Both methods employ the inertia and dynamic state of the MAAL strand to disrupt threat projectile. The mass approach to progressive scaling involves simply placing more mass in the trajectory of the threat projectile. Inertial progressive scaling, in contrast, employs selectively tuned MAAL strands to create optimal yaw and pitch disruptions on the threat projectile. It does not necessarily employ a MAAL strand of heavier mass. This is operationally shown in Figure 101. Figure 91. in Chapter IV showed the efficacy of inertial progressive scaling in enhanced ballistic protection. The 40-1 MAAL (lighter) strand outperformed the heavier 40-3 MAAL strand. The increased ballistic performance in this instance was attributed to optimal inertial disruption by the 40-1 MAAL strand.



Inertial progressive scaling employs selectively tuned MAAL strands to create optimal yaw, pitch, and roll disruptions on the threat projectile to reduce its penetration. It does not necessarily employ a MAAL strand of heavier mass. The pictures in the figure show how the threat projectile embedded into the first catcher plate of the MAAL system yawed and pitched.

Figure 101. Adaptive Resilient Armor: Inertial Progressive Scaling.

Replacement, repair, and healing adaptations are essentially the same as redundant scaling. A damaged MAAL strand can be replaced or repaired using a strand of the same size. This in effect heals the vulnerable or perturbed portion of the armor system, restoring its functionality.

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VI. CONCLUSIONS AND FUTURE WORK

A. SUMMARY

As discussed previously, traditionally engineered systems are disadvantaged in complex operating environment. Many of these systems lack the ability to maintain agile top-level functionality in situations of rapid and significant requirement perturbations. This is disadvantageous because in complex operating environments, these systems are often placed in a reactionary and costly state of operation rather than in a proactive or adaptive position of strength. These systems lack the resilience in their design to resist or recover from the constantly changing requirements in complex operating environments. The purpose of this dissertation was to propose, demonstrate, and prove the validity, efficacy, and value of a methodology that integrates the attribute of adaptive resilience into these systems.

Adaptive resilience enables a system to adapt its functional traits, structure, process, and/or identity in order to maintain or remain functionally effective in achieving its top-level functional requirements in complex operating environments. In order to achieve an adaptive resilient system, system designers and engineers must appropriately identify, account for, and incorporate the necessary range of adaptive capacity for early in the design and development process. Thus, a comprehensive integration methodology was needed that accounted for appropriate adaptive design considerations during the system's design and development process.

This dissertation research falls into the field of resilience engineering, which is placed most appropriately as a subdiscipline of systems engineering. This field of study has existed in environmental, operational, and enterprise system contexts for decades. Volumes of prior work and art exist in these contexts, but very little work exists in the context of realizing resilience in technological systems. In these contexts, resilience was shown to be beneficial in the Apollo 13 mission as well as in the New York City power failures associated with the attacks of September 11, 2001. These examples represent instances in which enterprise systems were resilient to operational perturbations because they had the necessary adaptive capacity allowing them adapt to the situations. These cases highlight how resilience is

achieved through adaptability; adaptability is enabled through the creation of adaptive capacity. Adaptive resilience highlights the crucial link between these concepts and inextricably links them into a single system attribute that can be incorporated into the design.

This dissertation employed the fundamental steps of existing systems engineering and design processes as the basis for the MSIAR. These steps target, shape and apply the appropriate modes of adaptive capacity within a technological system; enabling it to achieve an enhanced state of functional resilience. This methodology can be used in standalone system design fashion or in a broader system design context that includes many attribute designs. The methodology consists of seven steps, each of which is binned under a fundamental step of the systems engineering process. The seven steps are as follows:

1. Define adaptive design considerations
2. Identify controllable/adaptive performance factors
3. Characterize adaptive performance factor configurations
4. Verify and validate adaptive performance factor configurations
5. Map validated configurations to adaptive system components/modules
6. Integrate adaptive components and configurations into system
7. Verify and validate integrated component configurations and performance

These steps were explained in detail in Chapter III. In Chapter IV, the steps were applied in a relevant case study involving the design of an adaptive resilient armor system. The case study used requirements from an existing CDD and decomposed them into adaptive design considerations. These constraints and considerations were used to identify controllable armor performance factors. These factors were then characterized and validated at achievable design configurations, mapped to components, integrated into a system, and verified and validated through ballistic experiments. The results of these experiments, as well as a conceptual integration model, were presented in Chapter V.

B. CONCLUSION

The methodology for the system integration of adaptive resilience is shown to be a sound methodology for the creation of adaptive capacity within armor systems. The MSIAR enables technological systems to adapt physical component performance factors and realize a resilient state of operation in complex environments. This methodology was applied to the design of an adaptive resilient armor system, which served as a case study proof of concept for the methodology. This system was based on relevant operational requirements (GCV CDD) where, in a static traditional or contemporary system design, the top-level function would be at odds with other critical functions for the greater system of systems. The adaptive capacity, shaped by the three adaptive design considerations, provided the armor system component-level adaptability. This adaptability enabled the system to meet the top-level function of vehicle protection, while mitigating consequential parasitic capacity on adjacent functions such as vehicle mobility and transportability. This result is summarized in Table 8. The armor system provided a range of ballistic protection that handily met both the threshold and objective requirements. If the system's ballistic protection state was suddenly insufficient to meet an evolving threat the host platform was facing, the integrated adaptive capacity provided the armor means to rapidly adapt to a sufficient protected state (up to the objective threat requirement). This adaptive capacity was enabled through internally and externally reconfigurable means that adapted to known and characterized adaptive factor configurations. The adaptive means created the adaptive capacity, which is the only way to achieve the desired goal of creating an adaptively resilient system.

Table 8. MSIAR Results in Addressing the Adaptive Design Considerations

Adaptive Armor Design Constraints:		Results:
ADC 1:	The adaptive armor design must be able to prevent the penetrations of .30 cal APM2 threats at the threshold and .50 cal APM2 threats at objective levels through adaptive mode one (internal reconfiguration) and adaptive mode two (external reconfiguration) at 50% reduction of weight from a Fixed RHA Armor System. (T:24 psf; O: 40 psf)	Objective Threat Defeated at 16 psf.
ADC 2:	The adaptive armor design must achieve the maximum amount of ballistic protection from the least amount of weight.	See Above. Notional Objective Threat Defeated at 80% reduction in areal density from fixed armor system.
ADC 3:	The integrated adaptive resilient armor design while integrated on the host GCV platform may not exceed 204 inches of total GCV system width during strategic transport.	Prototype system buys back 36" of total vehicle width.

C. FUTURE RESEARCH

This dissertation serves as an initial foray into integrating the attribute of adaptive resilience into a technological system. The proposed methodology merged concepts and principles from the maturing field of resilience engineering with system design and engineering principles. This methodology was demonstrated on a single case study involving the design of an adaptive resilient armor system, although it can be applied to any technological system that encounters complex operating environments and competing requirements. Future research efforts regarding the methodology should center on applying the methodology toward other systems that require adaptive resilience as a functional attribute. This future research should focus on refining the activities and processes associated with each step of the methodology.

Specific process steps that require further refinement are the verification and validation steps. Because this system is more complicated and arguably more complex than are traditionally engineered systems, the verification and validation processes are also more complicated and complex. In the verification process, the complication and complexity arises even if the adaptations do not implicate other system aspects or performance requirements. Alternatively, if they do implicate these other system attributes, what level of implication is acceptable? This is a challenging; this methodology motivates its users to include factors that are more adaptive, thus making the system more resilient to top-level function failure.

However, with increased adaptive means, the potential for consequences affecting other systems grows.

In addition, future research should focus on objectively quantifying adaptive resilience. This is a highly complex question—the value to which adaptive resilience is measured is only applicable to the top-level function of interest. In addition, the two types of resilience, resistance and recovery, are disparate in their circumstances and do not easily support a cumulative measure of resilience. Further, the increase in technical system complexity inherently increases risk in the areas of reliability, availability, and maintainability of the technical components that enable the system adaptations to occur. These components allow the requirements to be more resilient to perturbation and failure but may introduce resilience faults because of the potential increase in complicated mechanisms. A means to capture the top-level functional resilience holistically in the context of reliability, availability, and maintainability concerns is an obvious follow-on step for future research.

This methodology also required the use of risk analysis to identify which level or scale of adaptive performance to place on a given system for its operating environment. In the context of an adaptive armor, an objective means to determine which protection level to employ for a given operation needs to be defined. The number of operational protection configurations presented to a commander are numerous. How does a commander determine where and when to apply a lighter or heavier version of the adaptive resilient armor system? When is mobility valued over protection? When is it wise to use a lower level of protection in the unknowable complex operating environment? Currently, these types of questions can only be subjectively answered based on the experience and judgement of the user. An objective way to define the appropriate adaptive configuration for a given complex operating environment is another area of future research that must be pursued for such a system capability.

This dissertation research resulted in the design of an actual adaptive resilient armor system with relevant and significant capability. This armor design was demonstrated in a proof-of-concept fashion and therefore requires further verification and validation. Detailed ballistic characterization that statistically validates efficacy in ballistic protection would serve as a first step. In addition, proofing the armor system against threats that are more lethal and

demonstrating the performance benefits of progressive and redundant scaling would be of value. Another intriguing result of this dissertation research was the significant difference in performance between the MAAL strand widths. The 40–1 MAAL strand significantly outperformed the 40–2 and 40–3 MAAL strands. There was contention among those who performed the tests whether this was the result of the different moments of inertia between the strand sizes, the mass impulse difference on the material mechanics of the projectiles after impact on the MAAL strands, or merely an anomalous experimental result. Further experimentation with more suitable measurement equipment for this experimental end could solve this intriguing question.

This methodology may inspire many applications for integrating adaptive resilience into technological systems. These questions and many more will arise as this approach to systems engineering and design is further expanded and employed. Adherence to the fundamental principles of systems engineering will serve as a guidepost in answering these complex questions. The methodology for the system integration of adaptive resilience has the potential to eliminate many of the system tradeoffs that have limited the functional utility of systems that operate in complex operating environments. The methodology also has the potential to enhance operational effectiveness of systems that continually encounter operational challenges that stress or overmatch their ability to maintain top-level functionality. With proper discipline and application, this methodology could enable users to significantly enhance the resilience of the systems they are designing.

EPILOGUE

THE NEED FOR ADAPTIVE RESILIENT SYSTEMS: A HYPOTHETICAL VIGNETTE ALTERNATE ENDING

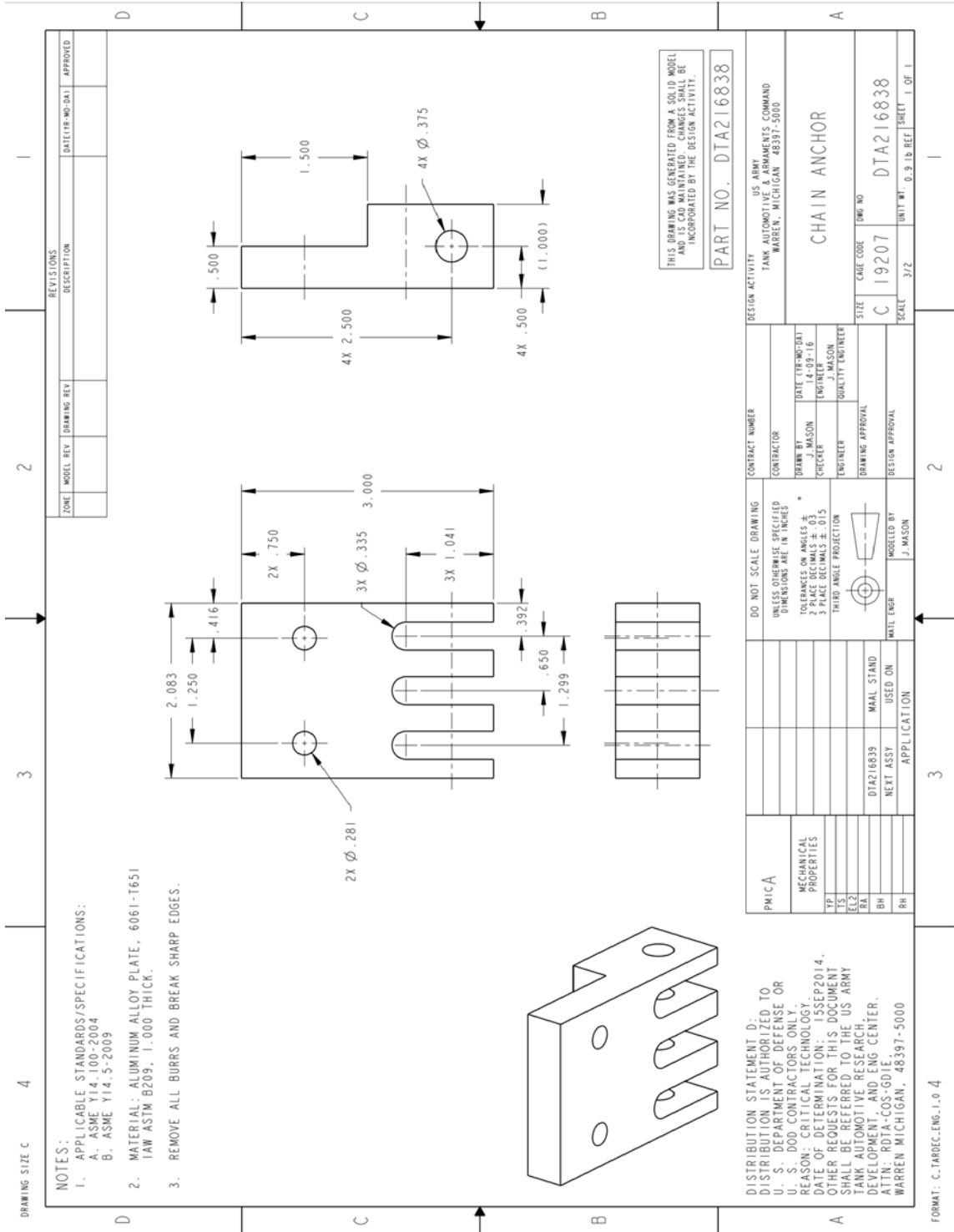
The crack of the PTRS-41 sniper rifle destroyed the brief calm of the Manekandow Valley. The dismounted patrol returned overwhelming fire at all suspected enemy fighting positions on the opposite side of the valley. However, the fire was ineffective. The sniper exfiltrated from his position before the patrol could return fire. A hidden photographer further up the valley recorded the incident and the actions of the Spartan Brigade Patrol. The gunner in the targeted HMMWV screamed for a medic. The patrol medic approaching the vehicle noticed a smoking hole in the driver-side door armor of the vehicle. The crew cabin was filled with smoke and screams. The gunner dropped from his cupola, still screaming. As the medic opened the passenger-side door, he saw the driver's door swing open. The HMMWV driver emerged hacking and coughing, uninjured from the antimateriel rifle's projectile. He ran to the passenger side to assist the medic. The gunner's leg was sprayed with spall and shrapnel, left when the projectile penetrated the vehicle—a minor but painful injury. The smoke erupting from the open doors was from a smoke grenade, which luckily had stopped the bullet before it struck the driver, a catastrophic result narrowly averted. The patrol leader approached the vehicle and looked at the gaping hole torn in the armor from the sniper's bullet. He radioed to the remaining vehicles of the patrol to adapt their armor systems to an increased level of protection enabled by the adaptive capacity integrated during the armor system's design. This change would likely implicate their mobility on the remainder of the patrol, but the added protection was worth it. Upon return to the patrol base, the patrol leader could debrief the Commander and make a recommendation to progressively scale the protection of their vehicles on future patrols with the available heavier armors. The enemy had adapted its tactics to counter the new armored vehicles. However, these vehicles were thoughtfully designed with adaptive resilience in mind. The fleet was ready to counter any adaption of conventional small- and medium-caliber ballistic threat the enemy could throw at them.

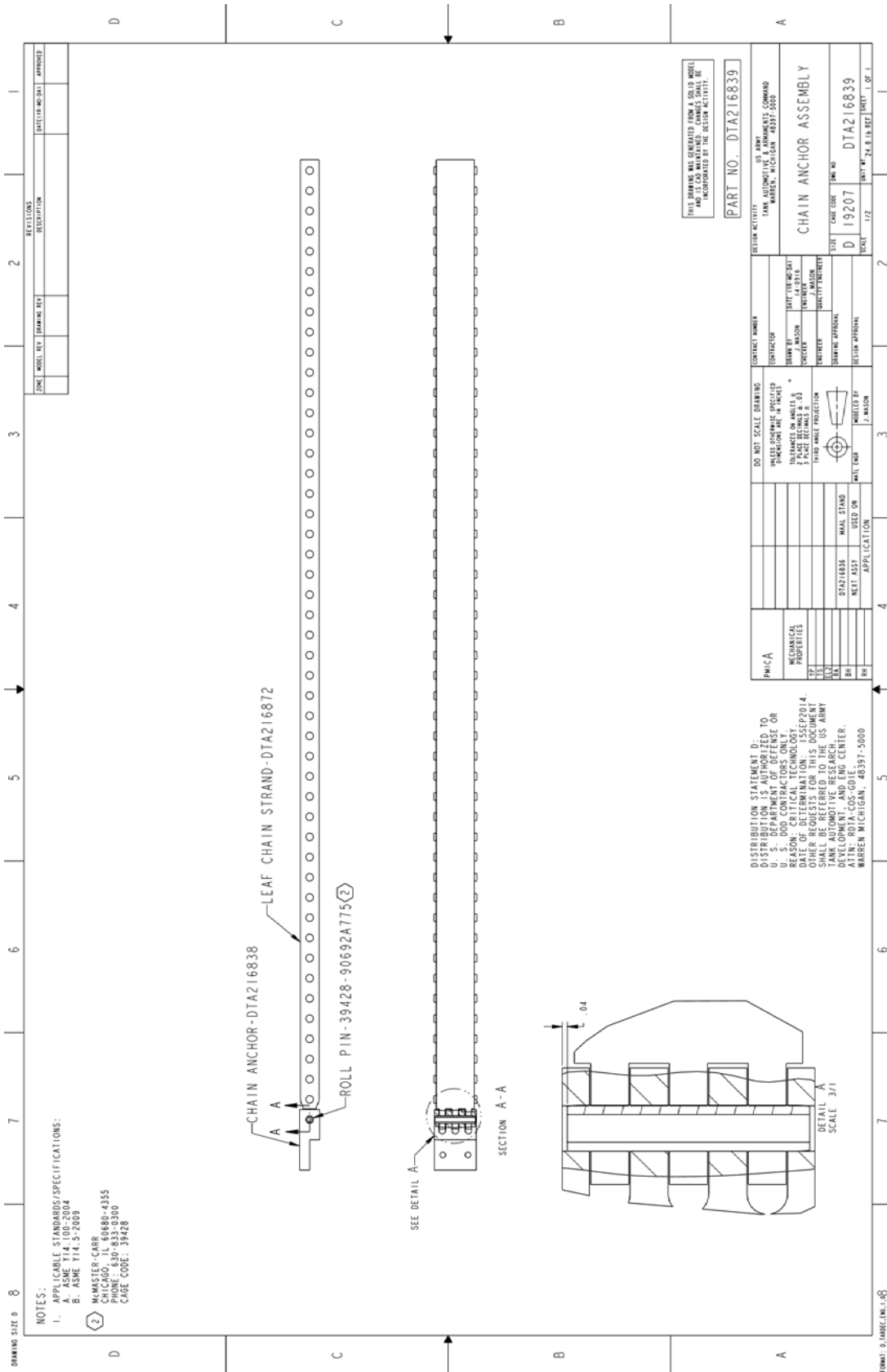
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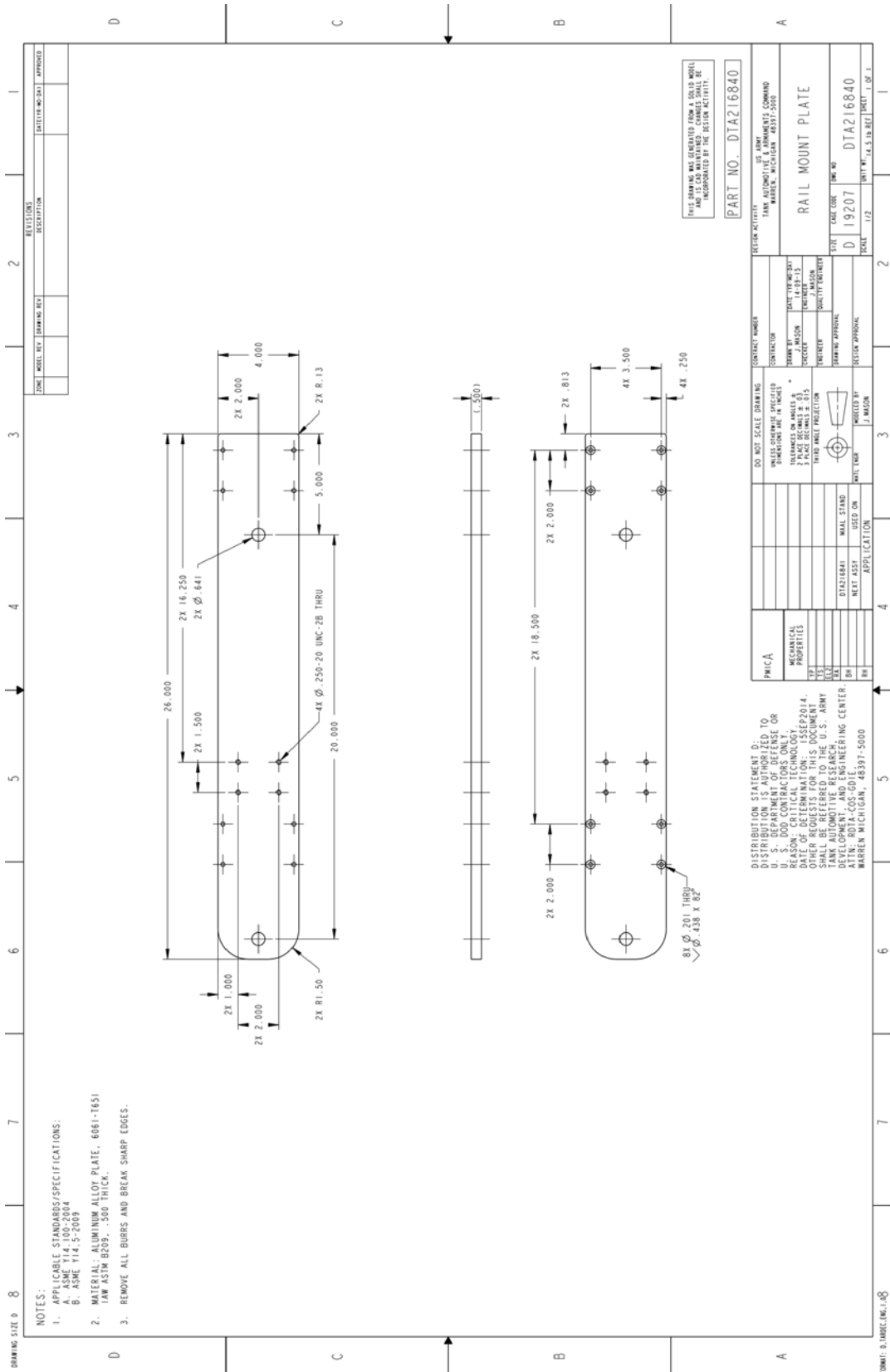
APPENDIX A. LEVEL 1 TECHNICAL DRAWING PACKAGE: MAAL DEMONSTRATOR

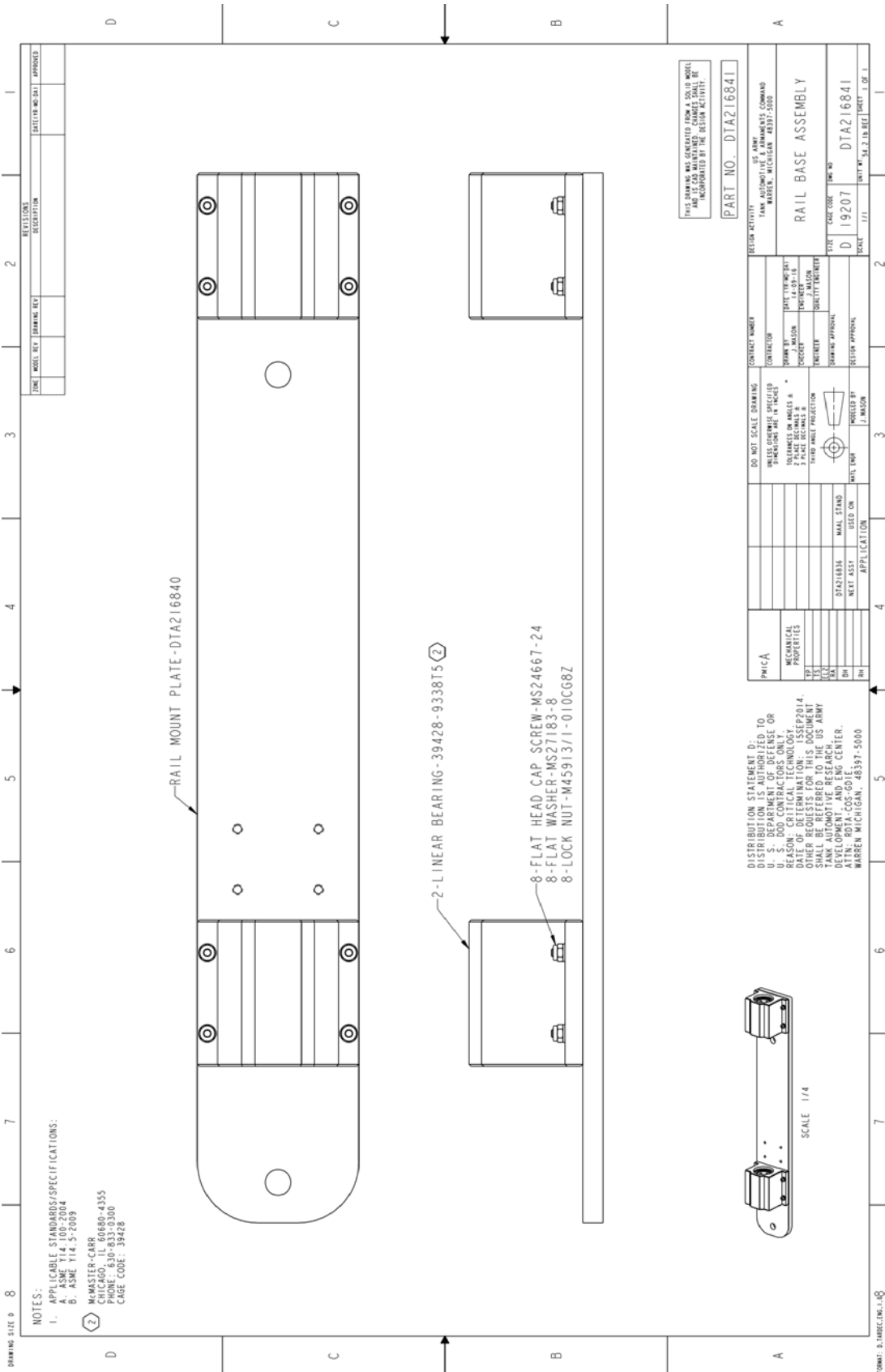
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3	2	DTA216837	DTA216836	19207	TOP PLATE	1	Part
4	2	DTA216841	DTA216836	19207	RAIL BASE ASSEMBLY	2	Assembly
5	3	DTA216840	DTA216841	19207	RAIL MOUNT PLATE	1	Part
6	3	9338T5	DTA216841	39428	LINEAR BEARING	2	Hardware
7	3	MS24667-24	DTA216841	19207	FLAT HEAD CAP SCREW	8	Hardware
8	3	MS27183-8	DTA216841	19207	FLAT WASHER	8	Hardware
9	3	MS45913/1-010CG8Z	DTA216841	19207	LOCKNUT	8	Hardware
10	2	DTA216932	DTA216836	19207	ACTUATOR MOUNT WELDMENT	2	Weldment
11	3	DTA216844	DTA216932	19207	ACTUATOR MOUNT ARM	1	Part
12	3	DTA216931	DTA216932	19207	ACTUATOR MOUNT REINFORCEMENT	1	Part
13	2	MS27183-10	DTA216836	19207	FLAT WASHER	40	Hardware
14	2	MS35338-44	DTA216836	19207	LOCKWASHER	40	Hardware
15	2	B1821BH025C100N	DTA216836		HEX SCREW	40	Hardware
16	2	95647A141	DTA216836	39428	PLASTIC WASHER	2	Hardware
17	2	91259A119	DTA216836	39428	SHOULDER SCREW	1	Hardware
18	2	MS27183-18	DTA216836	19207	FLAT WASHER	4	Hardware
19	2	MS35338-48	DTA216836	19207	LOCK WASHER	4	Hardware
20	2	B1821BH050C150N	DTA216836		HEX SCREW	2	Hardware
21	2	DTA216842	DTA216836	19207	ROD ASSEMBLY	2	Assembly
22	3	DTA216875	DTA216842	19207	ROD END ASSEMBLY	1	Assembly
23	4	DTA216843	DTA216875	19207	ROD END	1	Part
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25	3	95475A720	DTA216842	39428	STUD	1	Hardware
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30	3	DTA216872	DTA216839	19207	LEAF CHAIN STRAND	1	Assembly
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38	2	98335A127	DTA216836	39428	HITCH PIN CLIP	4	Hardware
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45	2	5913K64	DTA216836	39428	BASE MOUNT BALL BEARING	5	Hardware
46	2	DTA216948	DTA216836	19207	NUT PLATE	5	Part
47	2	MS27183-14	DTA216836	19207	FLAT WASHER	34	Hardware
48	2	MS35338-46	DTA216836	19207	LOCK WASHER	10	Hardware
49	2	B1821BH038C100N	DTA216836		HEX SCREW	10	Hardware
50	2	1497K101	DTA216836	39428	KEYED SHAFT	1	Hardware
51	2	1497K961	DTA216836	39428	KEYED SHAFT	1	Hardware
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59	3	M45913/1-4CG8Z	DTA216849	19207	LOCK NUT	14	Hardware
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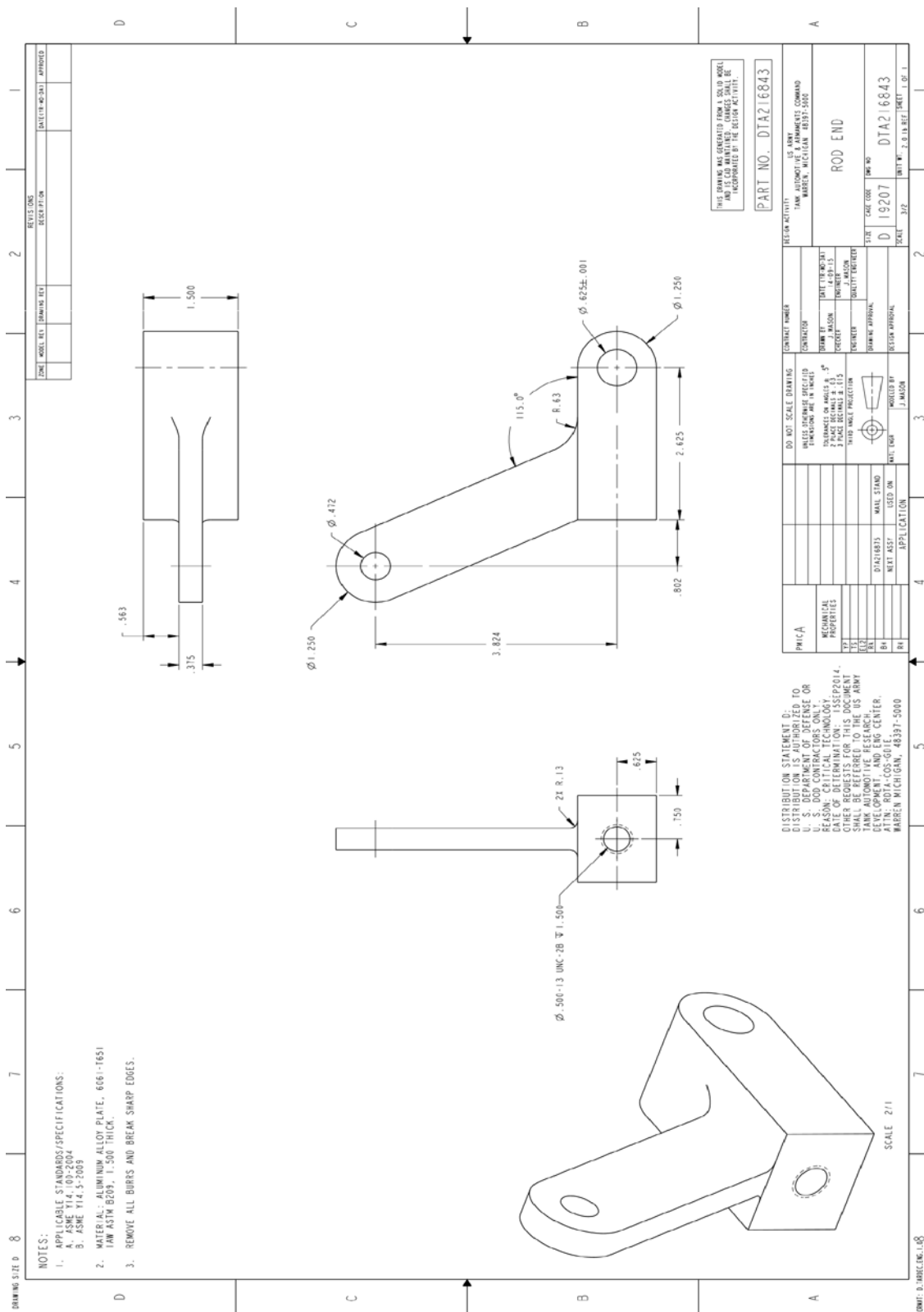
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65	3	40-3 RIV CHAIN	DTA217096	2B510	CHAIN STRAND	10	Hardware
66	2	DTA217097	DTA216836	19207	CHAIN STRAND, #40-1	1	Assembly
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68	3	6261K263	DTA217097	39428	OFFEST LINK	1	Hardware
69	3	6261K193	DTA217097	39428	STRAIGHT LINK	1	Hardware
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71	2	91202A238	DTA216836	39428	LOCK WASHER	16	Hardware
72	2	91280A527	DTA216836	39428	HEX SCREW	16	Hardware
73	2	B1821BH038C250N	DTA216836		HEX SCREW	12	Hardware
74	2	M45913/1-6CG8Z	DTA216836	19207	LOCK NUT	12	Hardware
75	2	DTA216954	DTA216836	19207	INDEX PLATE	1	Part
76	2	6435K18	DTA216836	39428	SHAFT COLLAR	1	Hardware
77	2	DTA216949	DTA216836	19207	HANDLE ASSEMBLY	1	Assembly
78	3	DTA216950	DTA216949	19207	HANDLE WELDMENT	1	Weldment
79	4	DTA216952	DTA216950	19207	COUPLER, MODIFIED	1	Assembly
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81	4	DTA216953	DTA216950	19207	HANDLE PLATE	1	Part
82	3	6308K44	DTA216949	39428	HANDLE	1	Hardware
83	3	MS35338-46	DTA216949	19207	LOCK WASHER	1	Hardware
84	3	12387305-9	DTA216949	19207	HEX NUT	1	Hardware
85	3	DTA216951	DTA216949	19207	KEY	1	Assembly
86	4	98510A136	DTA216951	39428	KEY STOCK	1	Hardware
87	3	MS27183-7	DTA216949	19207	FLAT WASHER	1	Hardware
88	3	MS35206-246	DTA216949	19207	MACHINE SCREW	1	Hardware
89	2	90293A139	DTA216836	39428	QUICK RELEASE PIN	1	Hardware
90	2	DTA217083	DTA216836	19207	BRACKET	1	Part
91	2	2236K14	DTA216836	39428	CONTROL BOX	1	Hardware
92	2	2236K16	DTA216836	39428	HAND SWITCH FOR TWO ACTUATORS	1	Hardware
93	2	MS27183-8	DTA216836	19207	FLAT WASHER	4	Hardware
94	2	MS35206-338	DTA216836	19207	MACHINE SCREW	2	Hardware
95	2	M45913/1-010CG8Z	DTA216836	19207	LOCK NUT	2	Hardware
97	1	39428-6051K16	6051K15	39428	CHAIN BREAKER TOOL	1	Tool

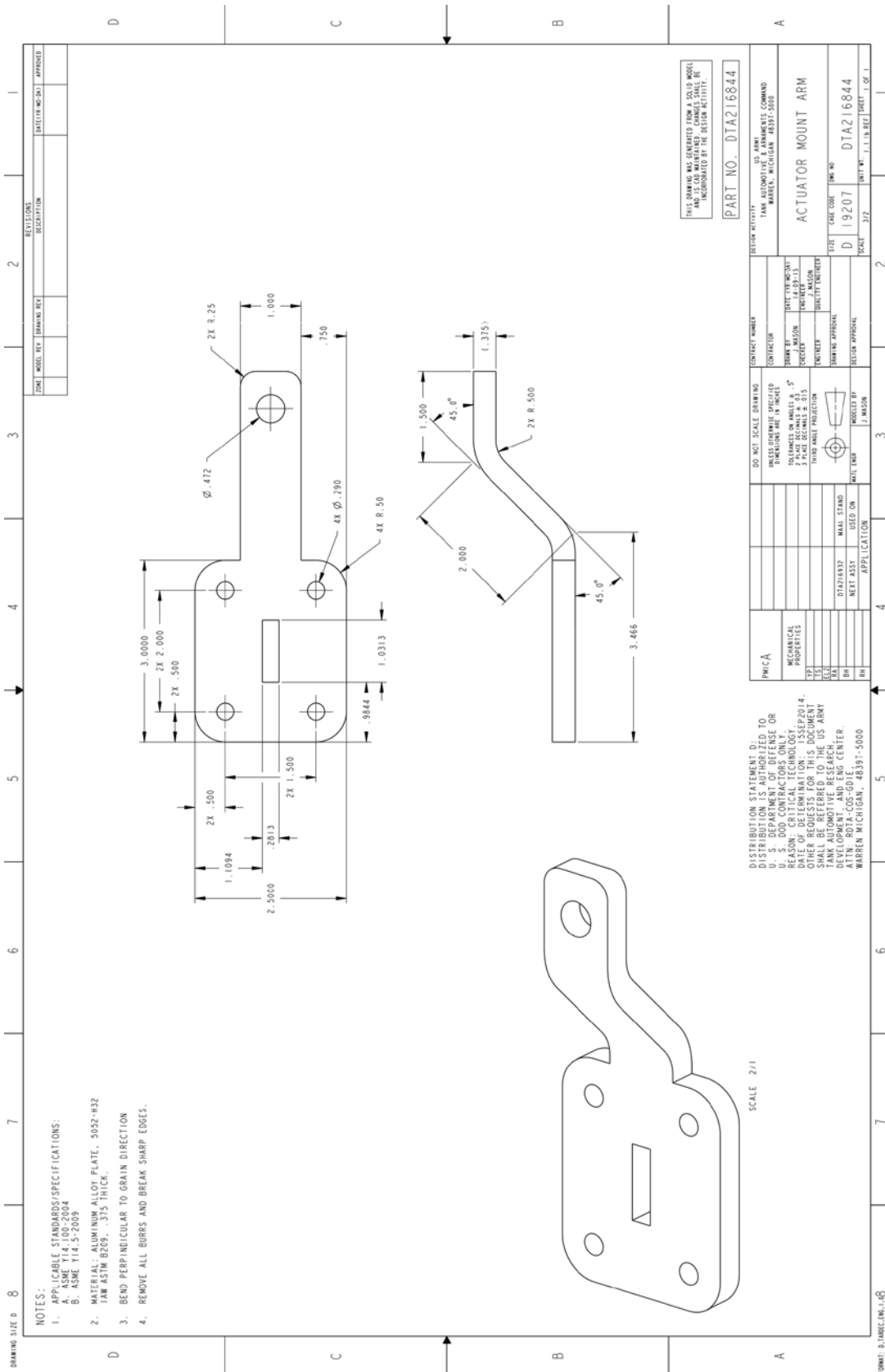


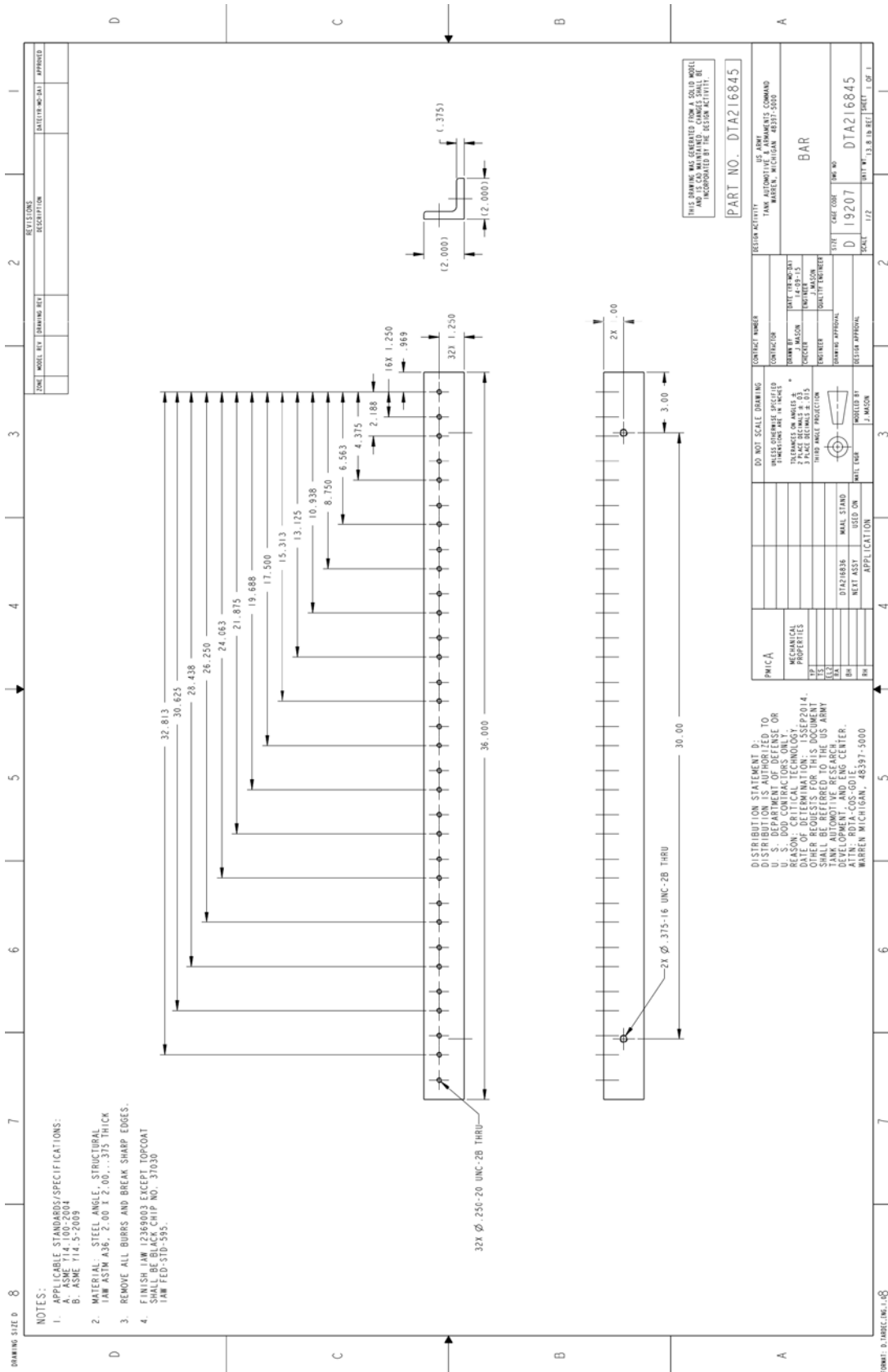


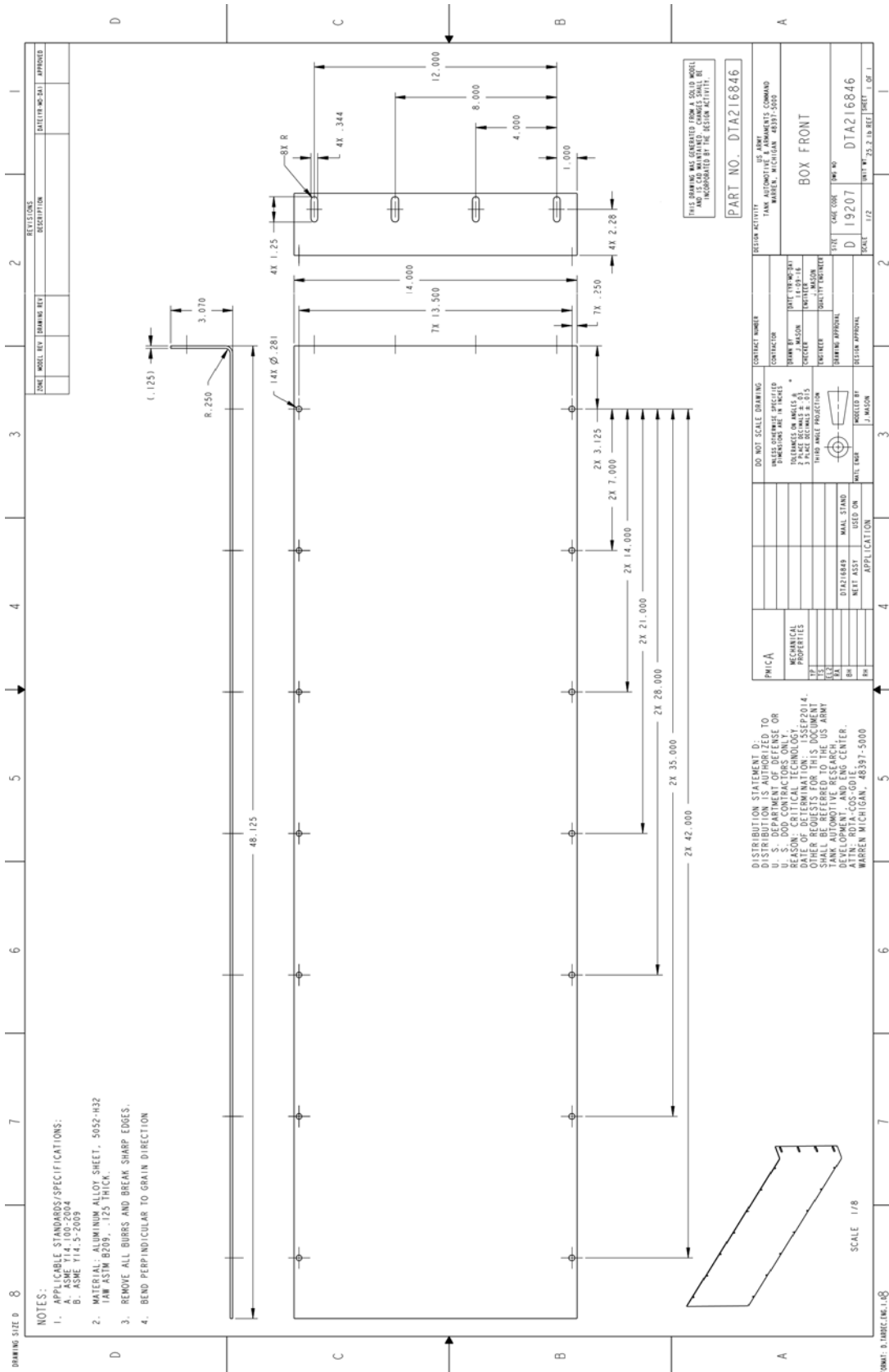




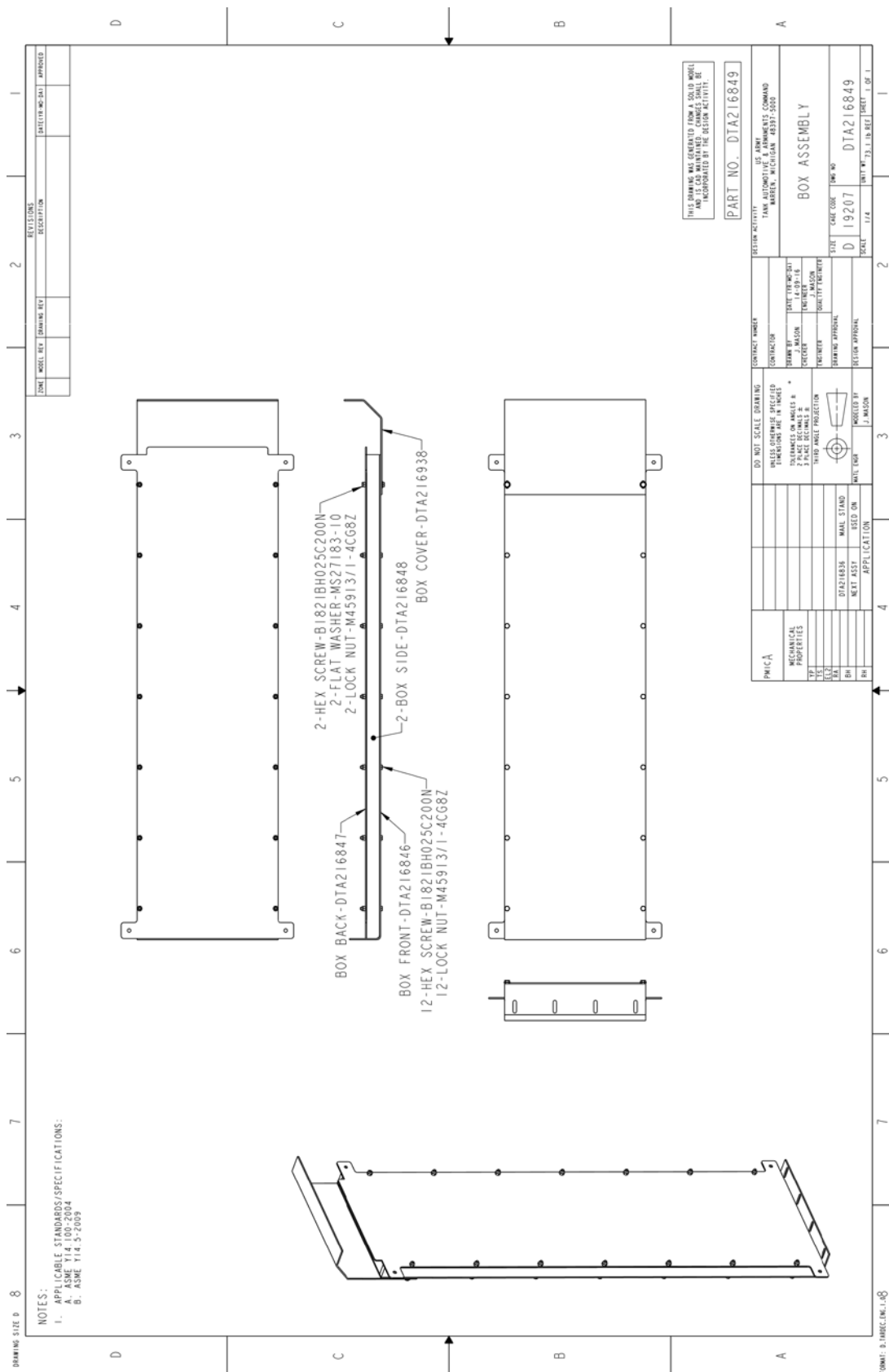


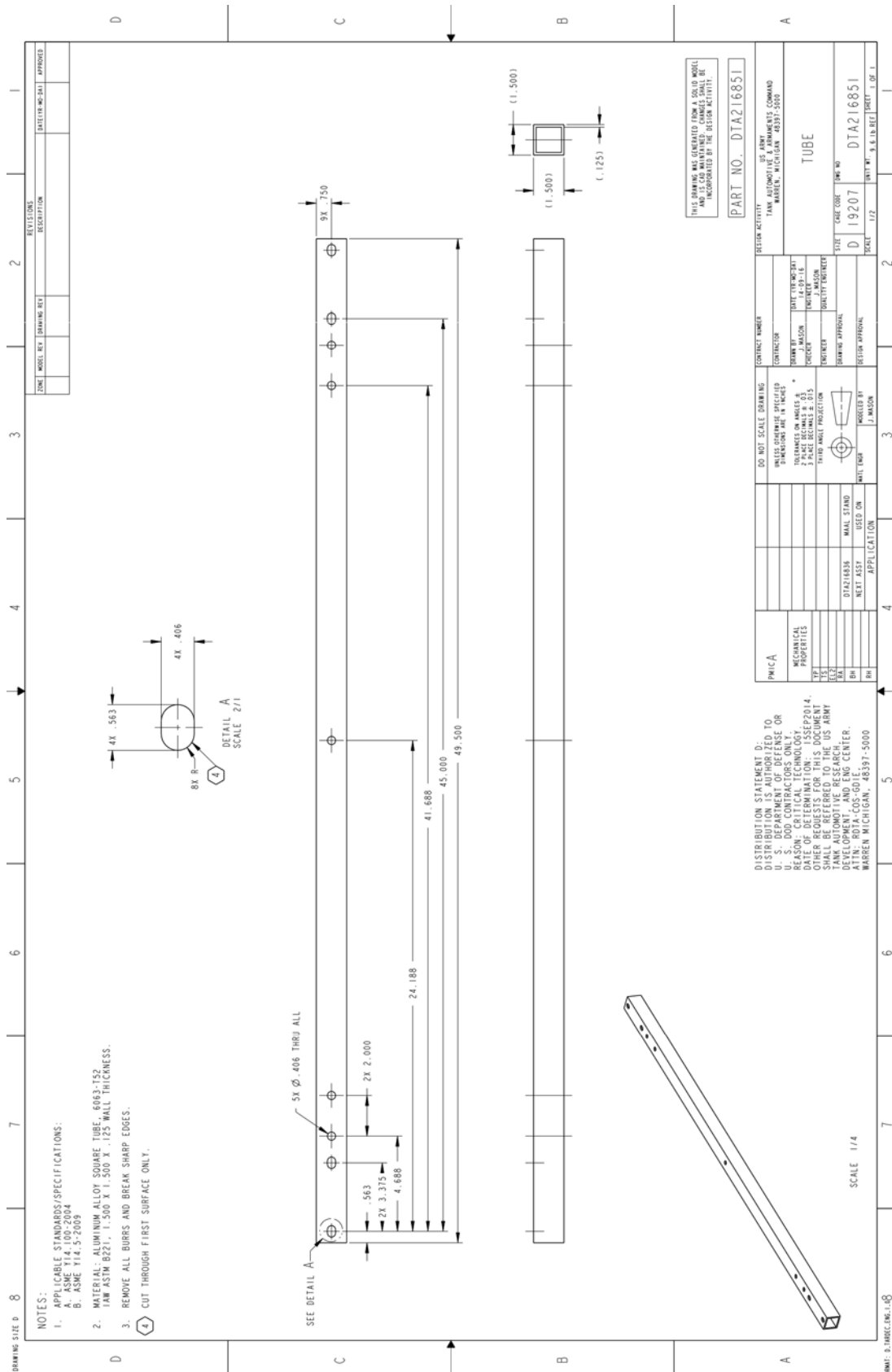


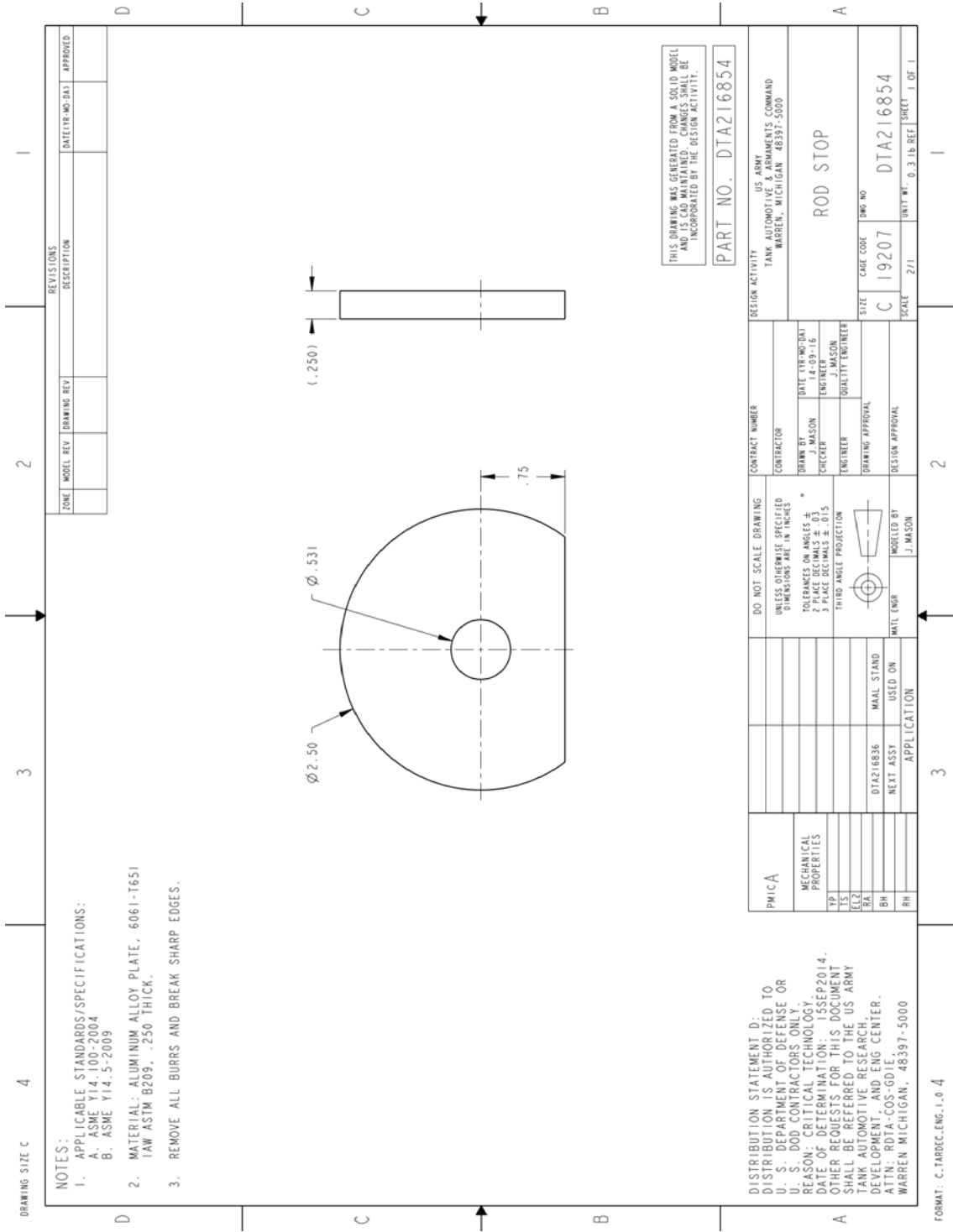




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DRAWING SIZE D 8

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NOTES:
1. APPLICABLE STANDARDS/SPECIFICATIONS:
A. ASME Y14.1-2004
B. ASME Y14.2-2005
2. NEWMASTER-CARR
CARRIAGE
PHONE: 630-833-8300
CAGE CODE: 39428
3. BEAM BEARINGS TO INDICATED
DIMENSION AFTER INSTALLING.

ROD END-DTA216843

Ø .501" ± .005 THRU (3)

2-FLANGED BEARING-39428-9440T37(2)

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AND IS AS MAINTAINED. CHANGES SHALL BE
INCORPORATED BY THE DESIGN ACTIVITY.

PART NO. DTA216875

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CONTRACTOR	WARREN, MICHIGAN 48397-5000
DATE	11-16-16
ENGINEER	J. WILSON
DESIGNER	J. WILSON
QUANTITY	2
SCALE	1:1
DATE	11-16-16
DESIGN APPROVAL	
DATE	11-16-16
DESIGNER	J. WILSON

PMCA	MECHANICAL
TP	PROPERTIES
TS	STRENGTH
TA	ANALYSIS
BM	BEHAVIOR
PH	PHYSICS
APPROVAL	
DATE	11-16-16
DESIGNER	J. WILSON

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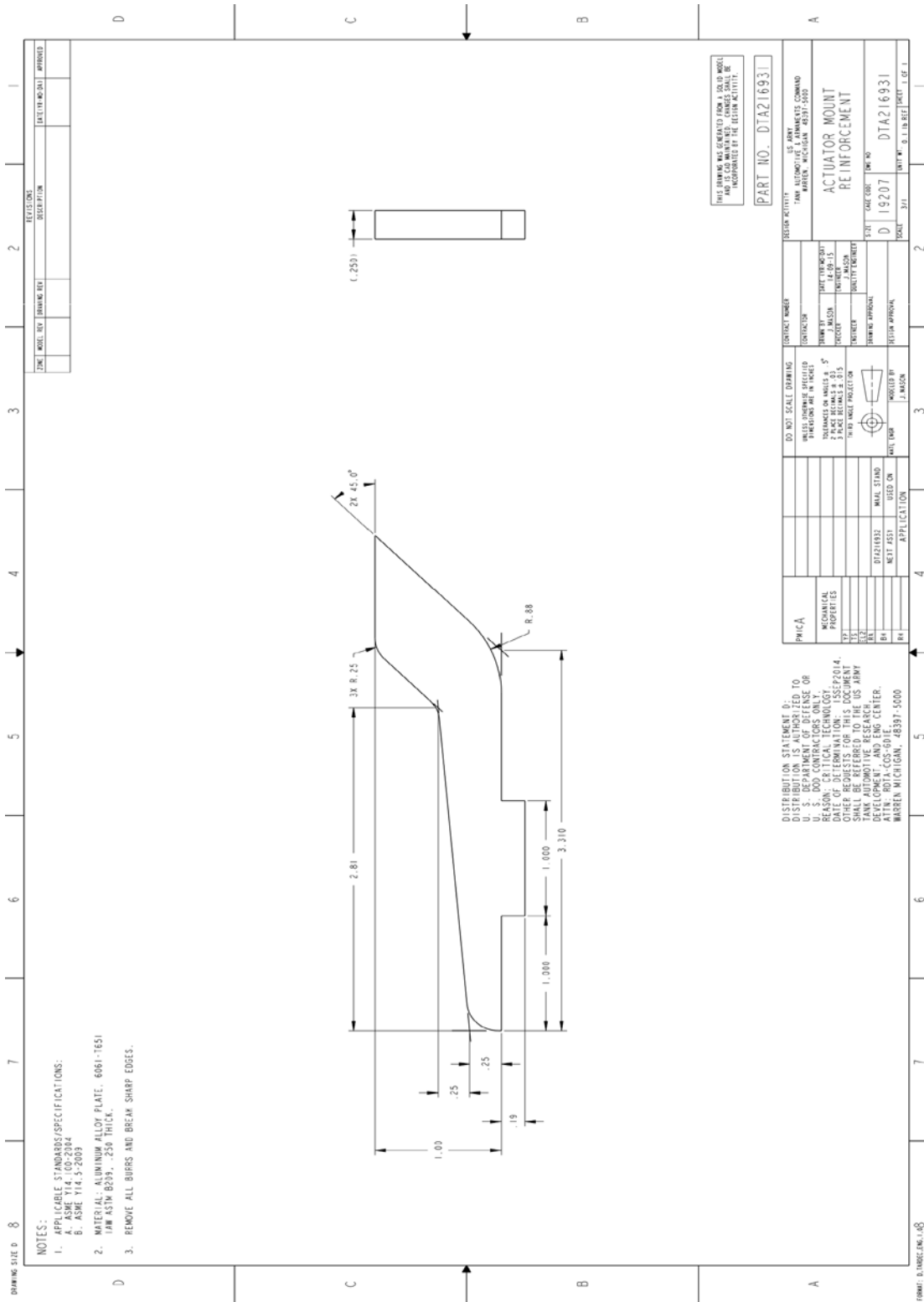
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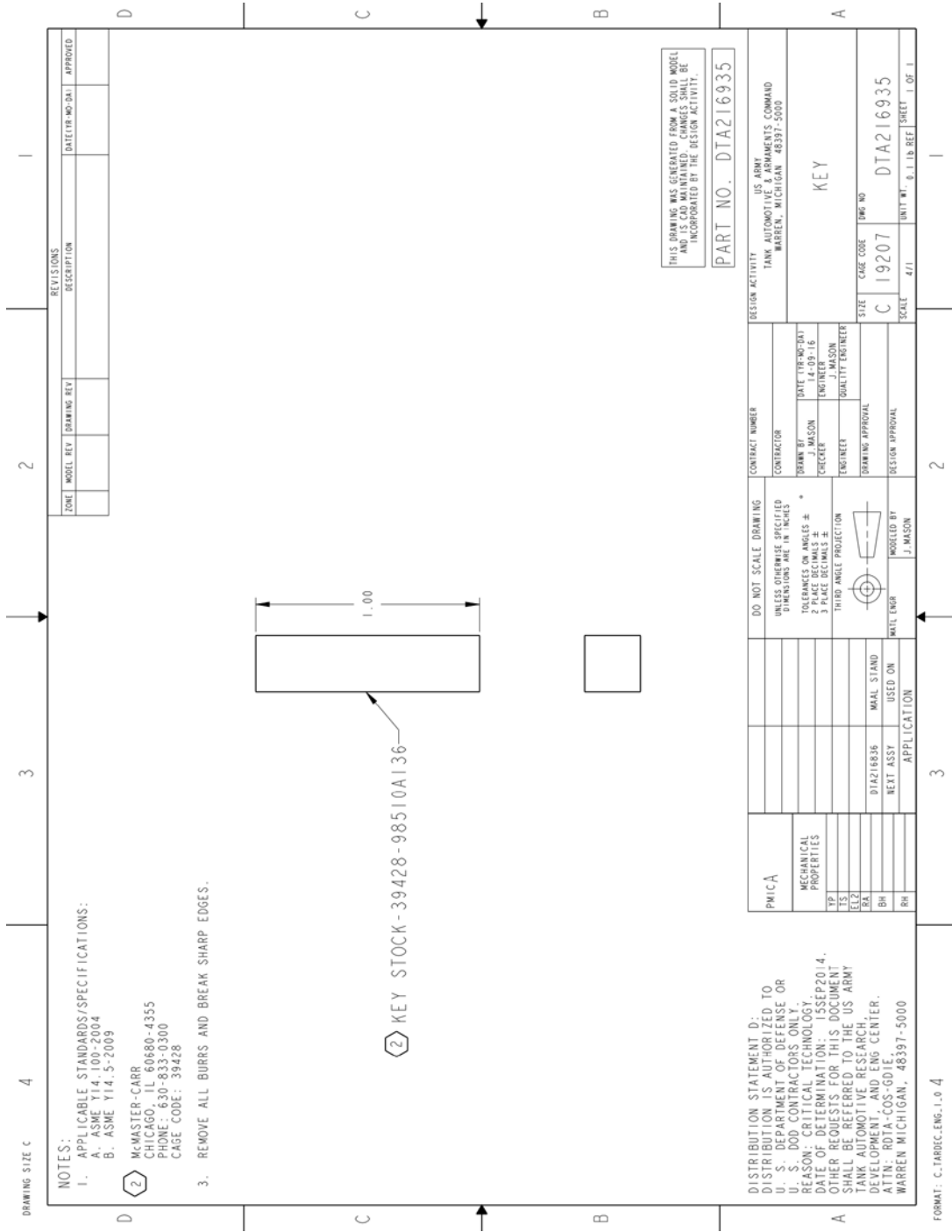
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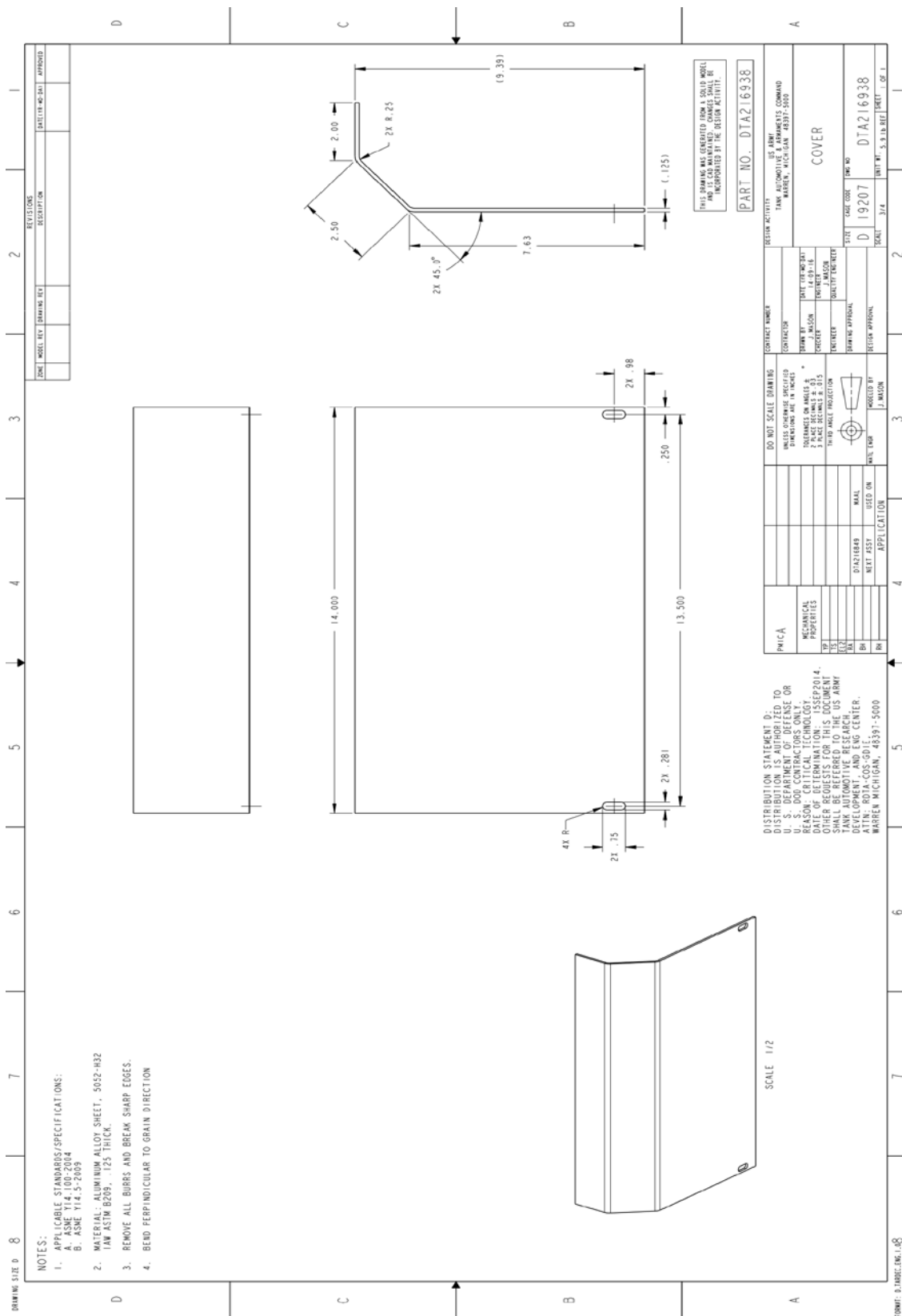
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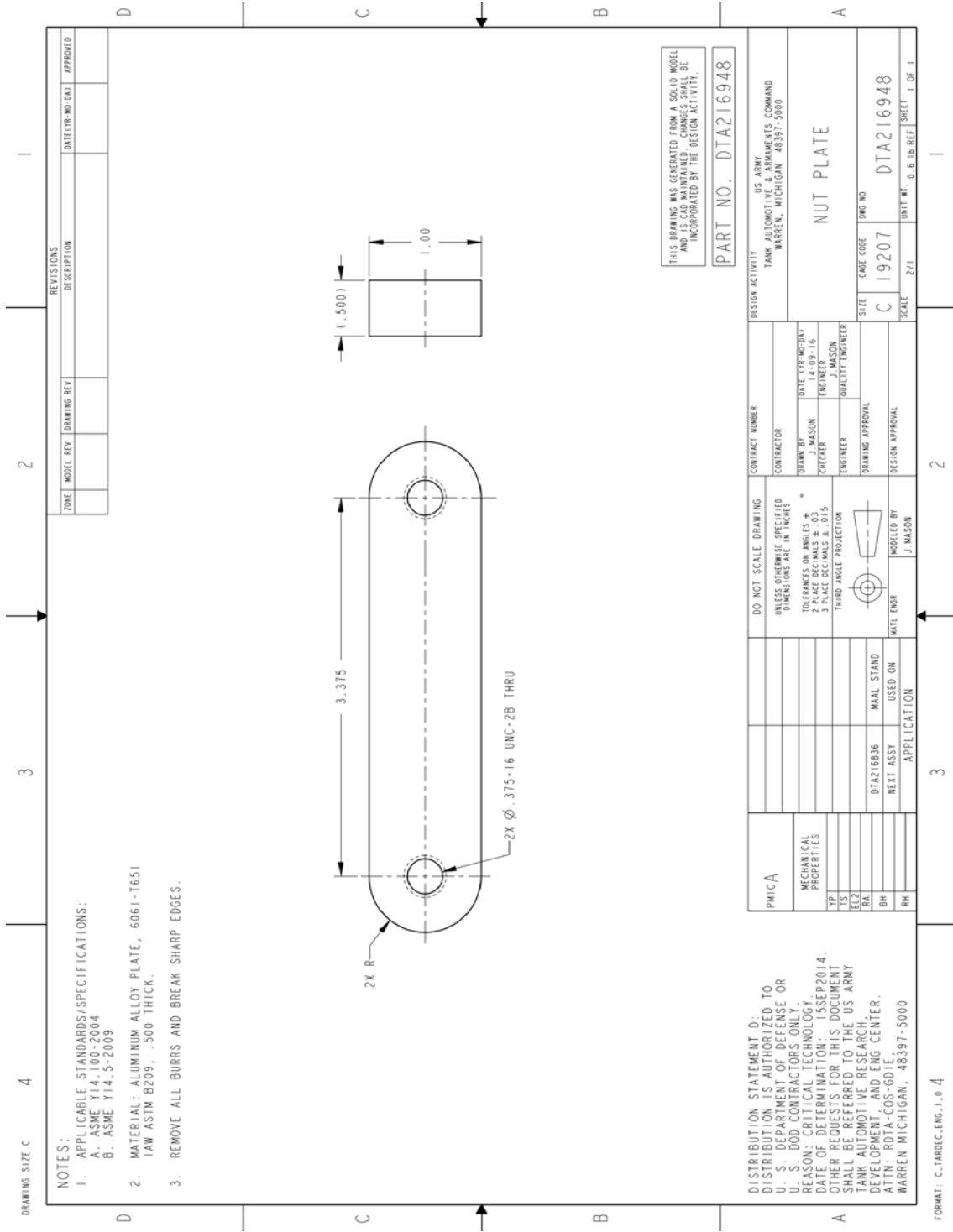
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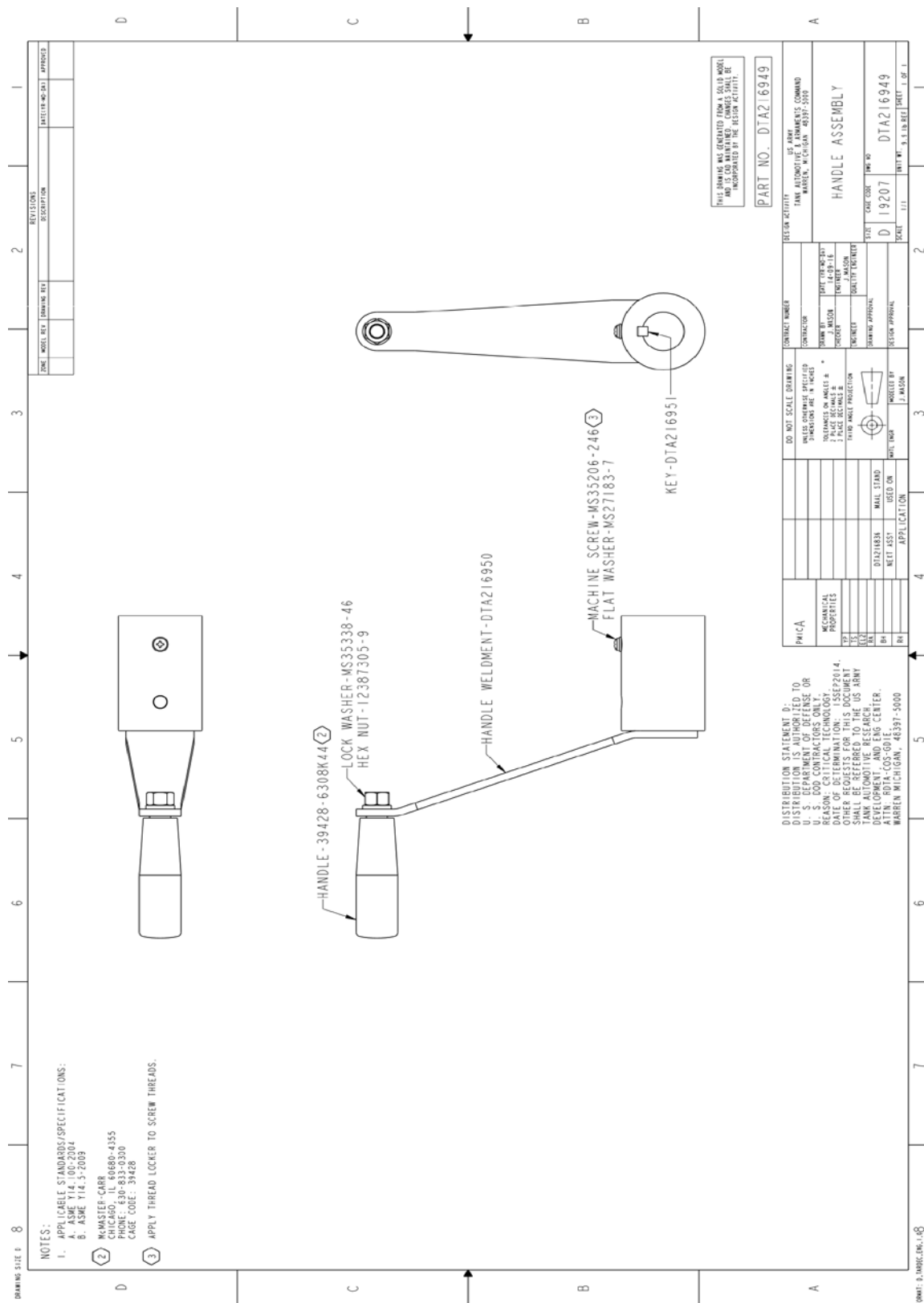
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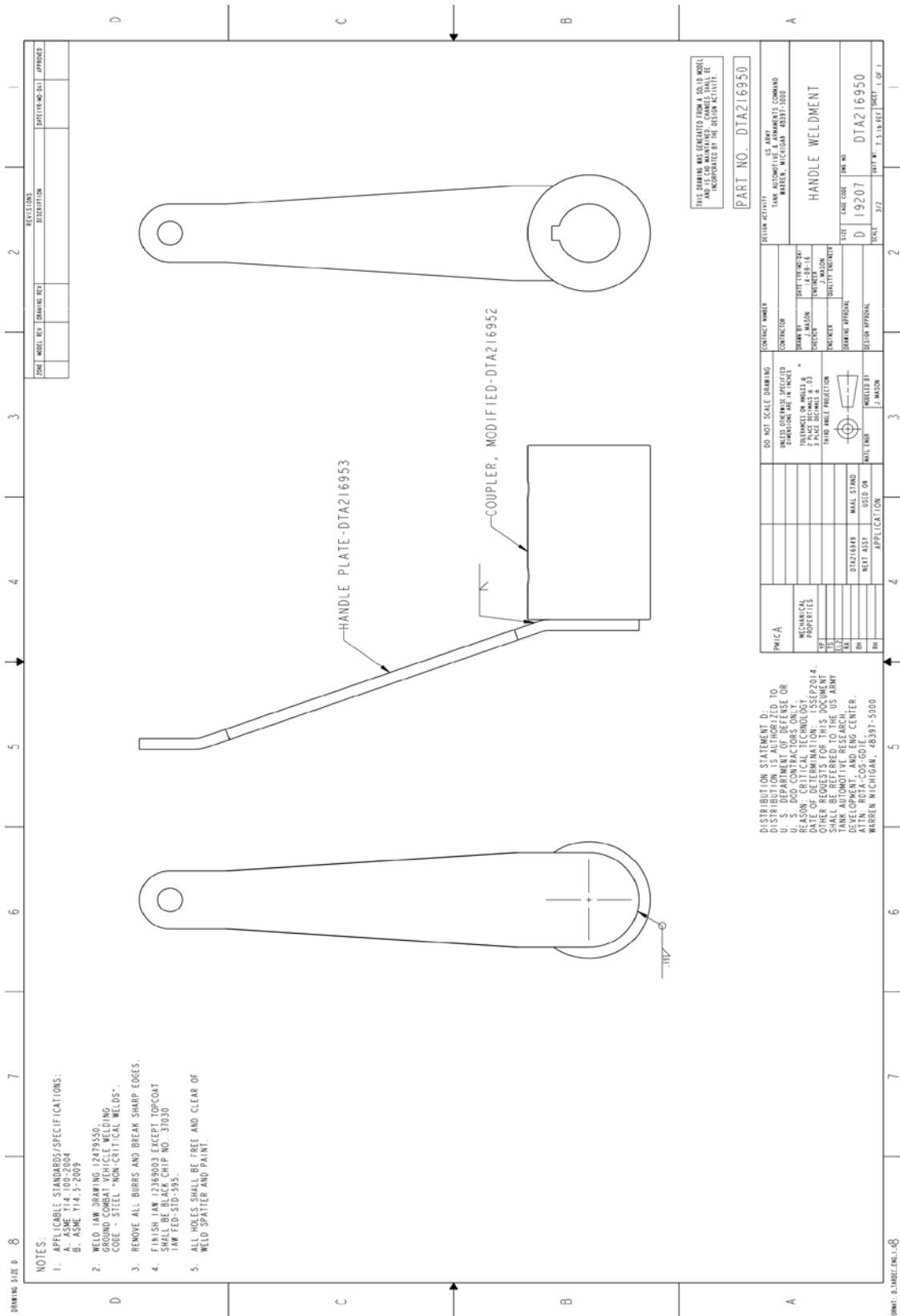


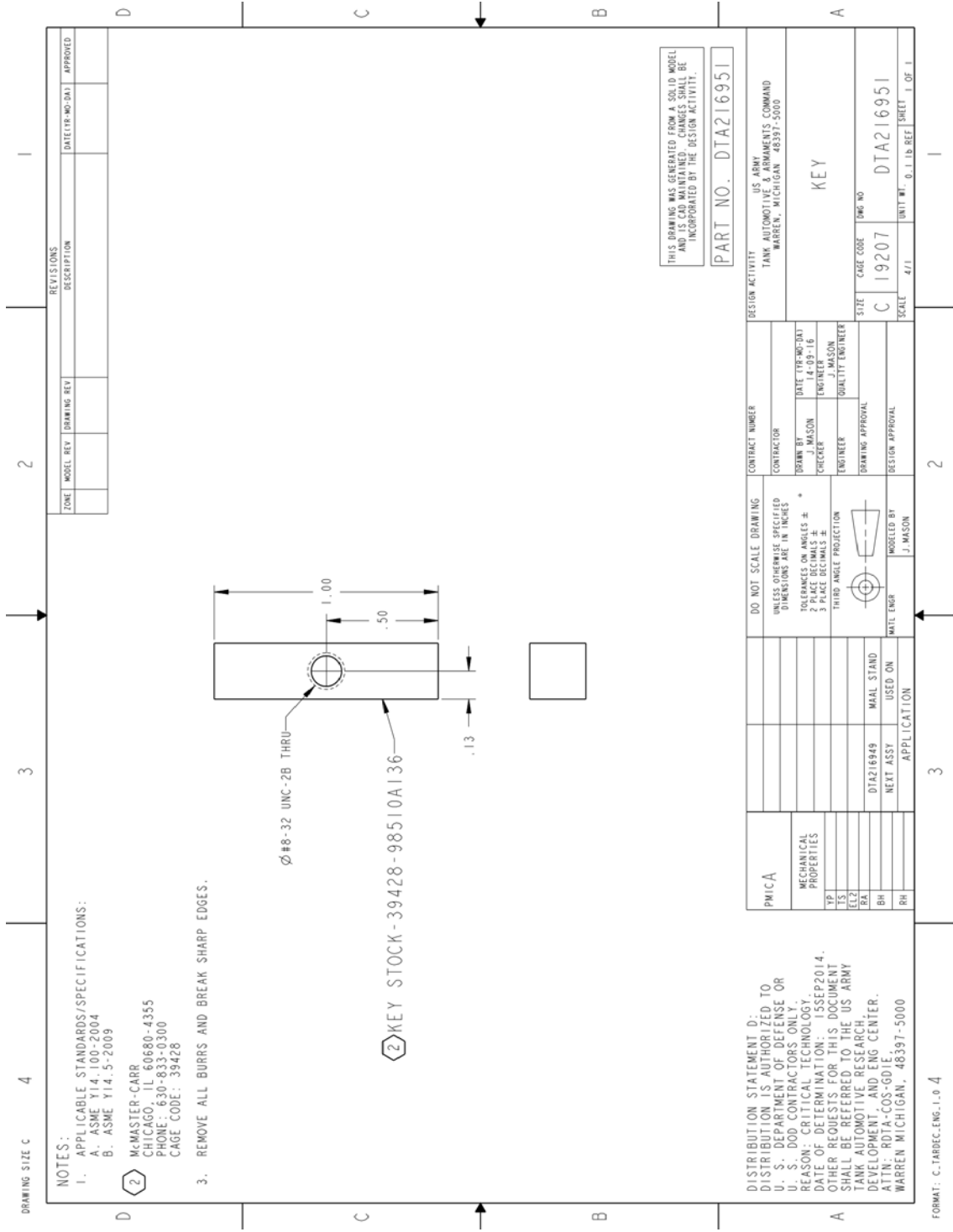


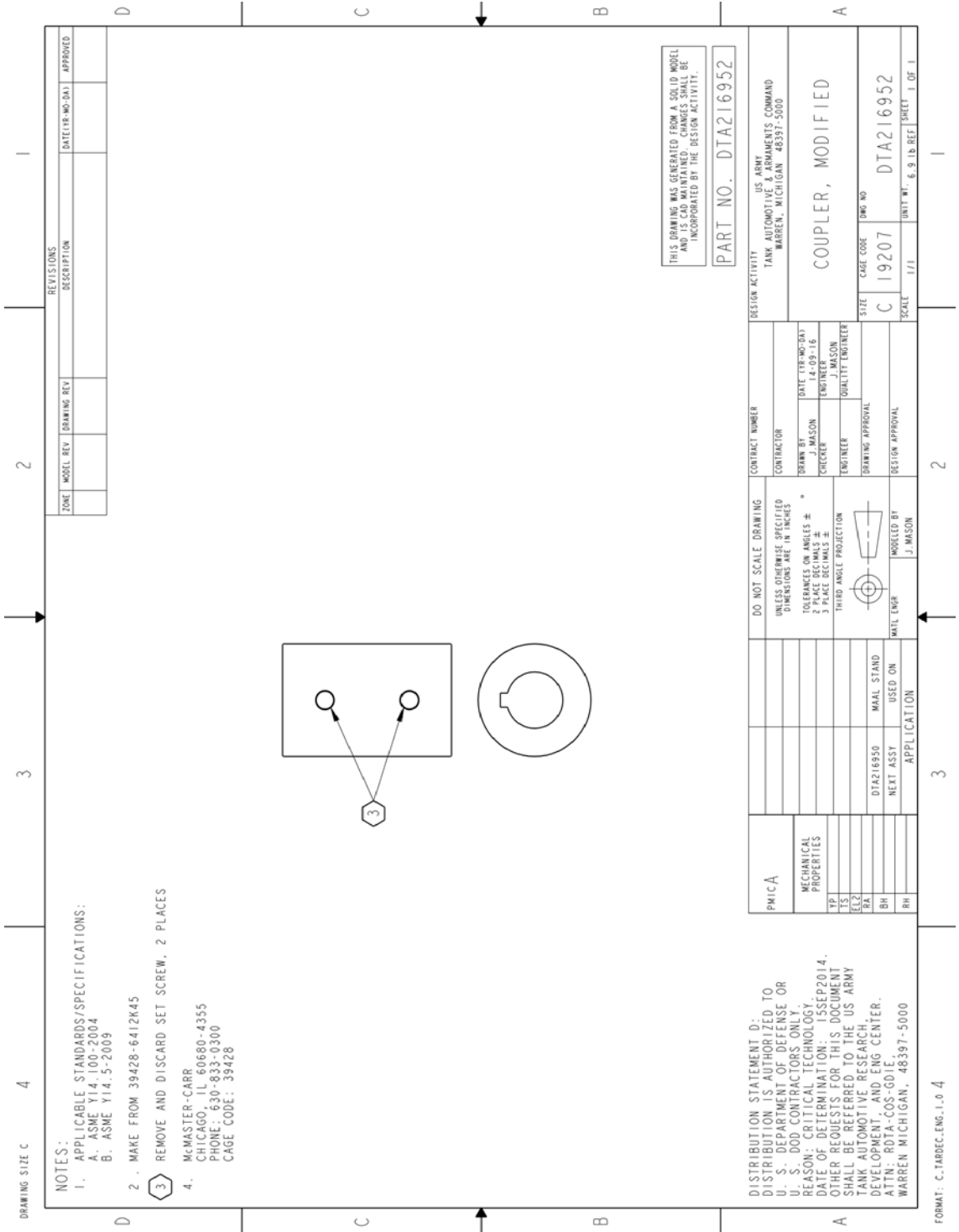


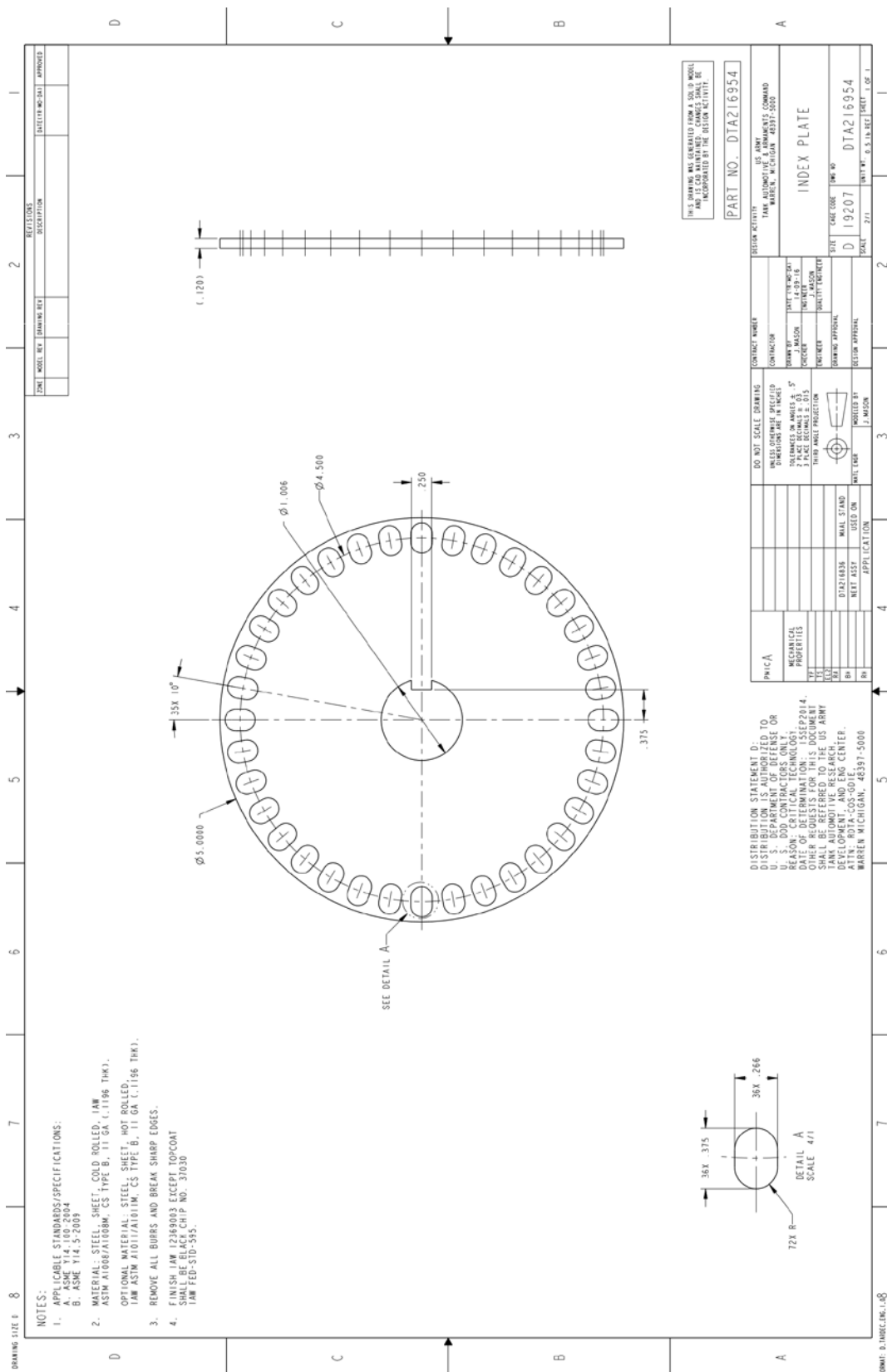


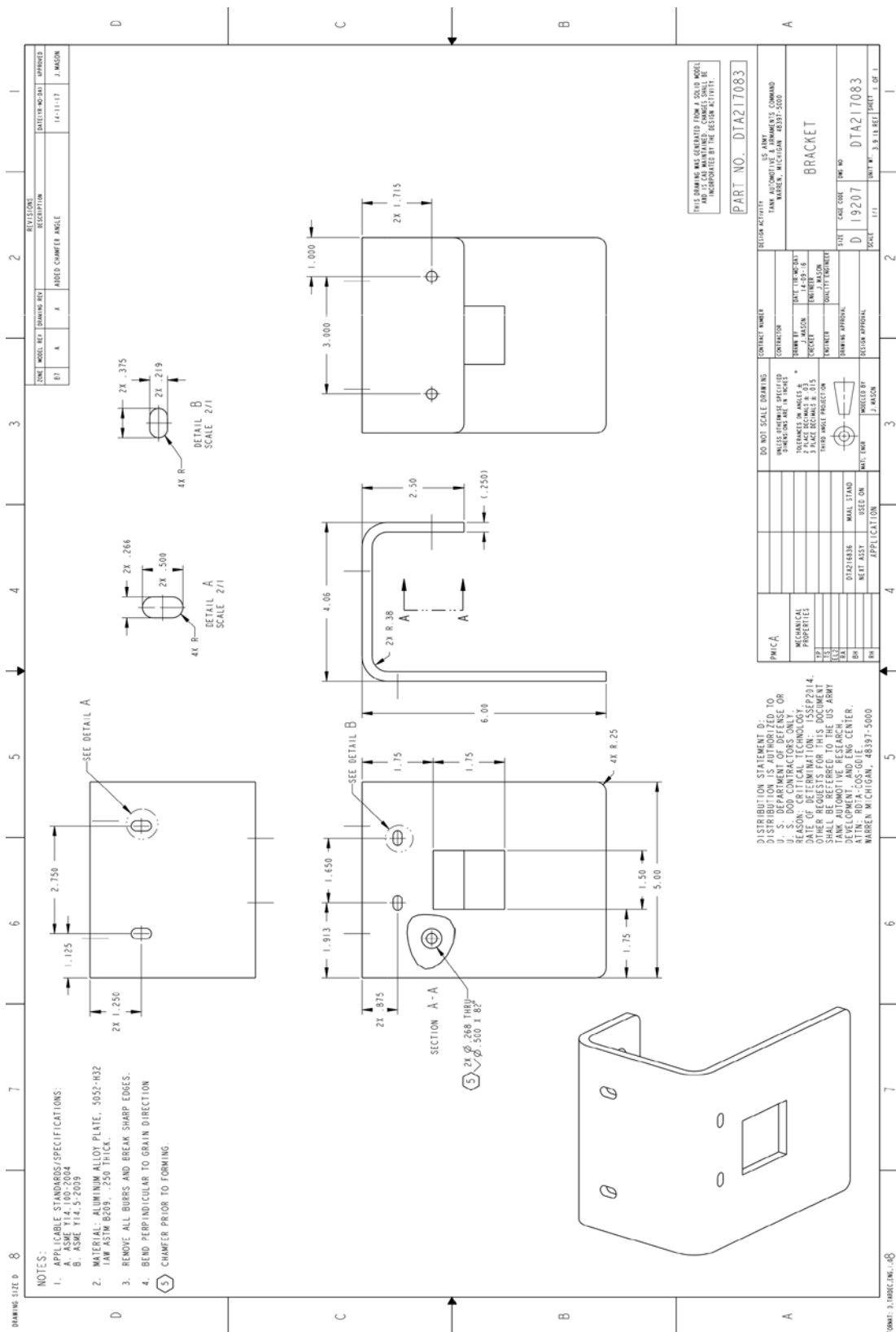












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APPENDIX B. BALLISTIC EXPERIMENT RESULTS

[illegible]

FACTORS	40-2																													
MIL DTL 32262 (AL WITNESS PLATE ONLY)																														
MIL DTL 41600 PLATE																														
40-1																														
40-2																														
40-3																														
80-L																														
.30 cal APM2																														
.50 cal APM2																														
AG 3"																														
AG 6"																														
AG 9"																														
AG 12"																														
AG 15"																														
AG 18"																														
OB 0°																														
OB 30°																														
OB 45°																														
OB 60°																														
1 Strand																														
2 Strand																														
3 Strand																														
Polycarbonate Backing																														
UHMWPE																														
Reallocation																														
% Threat KE Reduction	25.5	20.6	17.7	23	18.9	31																								
Areal Density	16	23	23	16	23	16	24	24	24	24	31	24	24	24	24	31	24	24	24	24	24	24	24	24	24	24	24	24	24	24
Column Totals:	46	48.6	45.7	43.5	46.9	51.5	94	63.3	45	175.8	51.5	79.9	70.8	67.2	108	132	92.4	82												
Mean % KE Reduction (MAAL)	40.30888889																													
Mean Areal Density	23.83333333																													
	19.35285714																													
	23.83333333																													

FACTORS	80-L				40-1		HH Plate								ALW					
	B15350-10	B15350-11	B15350-12	B15350-13	B15350-14	B15350-15	B15350-16	B15077-6	B15077-7	B15077-8	B15348-8	B15348-7	B15348-6	B15348-5	B15348-4	B15351-1	B15350-17	B15077-9	B15077-10	B15077-11
MIL DTL 33111 AL WITNESS PLATE ONLY								1	1	1	1	1	1	1	1	1	1		1	1
MIL DTL 41600 PLATE						1	1													
40-1																				
40-2																				
40-3																				
80-L	1	1	1	1	1															
.30 cal APM2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
.50 cal APM2	1	1	1	1	1	1	1				1	1	1	1	1	1	1			
AG 3"											1									
AG 6"												1								
AG 9"						1														
AG 12"					1	1		1	1	1										
AG 15"																				
AG 18"	1	1	1				1													
OB 0°	1			1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
OB 30°																1				
OB 45°																				
OB 60°		1	1	1	1											1				
1 Strand	1	1	1	1	1	1	1													
2 Strand																				
3 Strand																				
Polycarbonate Backing																				
UHMWPE																				
Reallocation																				
% Threat KE Reduction	22.5	20.2	54.3	30.9	18.7	6.66	6.66	30.53	32.82	31.4				22.7	9.99	37.8	36.53	1.58	2.7	2.1
Areal Density	33	29	29	33	29	19	15	40	25	25	63	48	33	33	33	25	18	38	38	38
Column Totals:	60	54	88.1	68.4	52.4	30.9	26.9	74.53	61.82	60.4	66.5	51.5	36.5	59.2	46.5	66.8	58.03	42.1	43.2	42.6
Mean % KE Reduction (MAAL)	29.314					6.66		31.59			26.7425							2.1266667		
Mean Areal Density	30.25					17.25		30			35.71428571							37.5		

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APPENDIX C. MAAL MATERIAL FAILURE ANALYSIS

ME 3202 Failure Analysis Project: Analysis of Modes of Failure for Adaptive Armor Chains Following Destructive Testing

By Tongli Lim, Tanya McKnight, Patrick Stewart, and Ken Foos, Naval Postgraduate School, Monterey, California, Spring 2016.

1. Failure Problem Background and Visual Observations

Our team's failure analysis project involved roller chain samples that were subjected to ballistic tests. This was a deliberate failure experiment in support of Mr. Joseph Cannon's doctoral dissertation and was conducted to support development of a new armor system called mechanically adaptive armor linkage (MAAL). In this application, the roller chains were used as a mechanical barrier to disrupt ballistic threats and prevent direct damage to its primary platform or vehicle.

The roller chains are manufactured by a U.S. company called Timken. The roller chains' primary function is to provide power transmission in mechanical drive mechanisms; the chains have an average service life of 15,000 hours. The chains are manufactured through heat treatment and range from 300 and 600 series stainless steel to nonstainless ANSI carbon steel. The roller chains consist of roller links, rollers, link plates, and pins. The rollers and link plates are shot peened for enhanced strength. Initially, the chain's material composition was uncertain. The temperature range during testing was the ambient temperature of the building, and anticipated use in the field did not exceed the 340°F threshold. Hence, the material properties in the catalog were used as a baseline for the material samples. There was no direct comparison between the estimated number of cycles to failure and the observed number of cycles because of the differences in anticipated loads and use. The samples were well greased, and no noticeable surface corrosion was seen. Observation of failure was documented by high speed, slow-motion video through top and side views. The videos clearly revealed that failure occurred from single ammunition rounds piercing through the samples. All projectiles approached orthogonal to the flatter side of the chains at speeds between 2800 and 2900 feet per second (fps). Tests varied between two strands of the MAAL with a 3" gap between with a 9" standoff from the aluminum witness (backing), two

strands of the MAAL back to back with a 9" standoff from the aluminum witness, or a single strand of the MAAL backed with a 0.065" polycarbonate cover and a 9" standoff distance. All chains were hung down freely in a vertical position, and all chains studied were hit by either a .30- or .50-caliber M2 armor piercing (AP) round. The moments of inertia of the chain varied in the samples, which led us to believe that one of the specimens could have experienced a greater plastic deformation than the other (less inertia and a greater deformation). More deformation is preferable as the projectile will expend more energy interacting with the chains, and the projectile's trajectory will be disrupted.

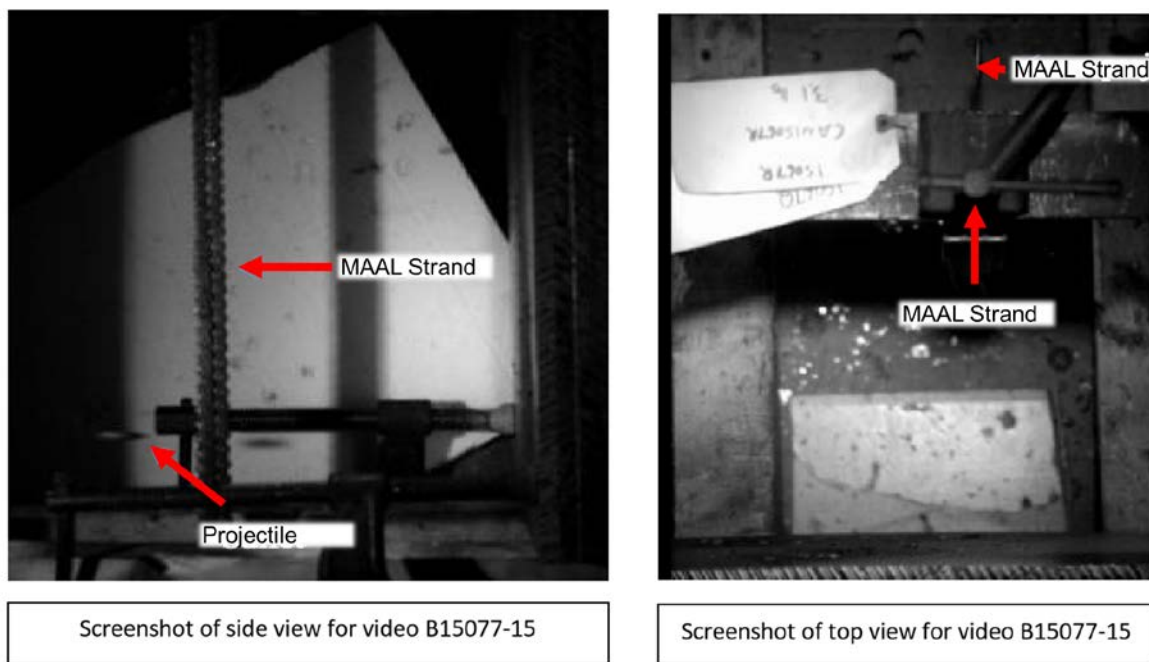


Figure App-1: Ballistic Test on MAAL.

Because of the high impact nature of the ballistic tests (see Figure App-2), the MAAL severed into multiple fragments upon impact by the rounds.



Screenshot of top view for video B15077-15 and screenshot of side view for video B15077-15.

Figure App-2: Screen Shots of Ballistic Test Carried Out on MAAL.



Figure App-3: Close up View of Parts to Be Analyzed.

Hence, the group narrowed the analysis to three parts of interest. Preliminary examination of these parts showed (a) fracture surfaces were not uniform; fractures were observed on the first, second, or third chain of both 40-2 and 40-3 chains; (b) plastic deformation on all three parts seemed to indicate ductile fracture of the MAAL; the plates appeared elongated prior to fracture; (c) fractures occurred at areas away from the impact site, indicating that energy from the round also dissipated to the rest of the MAAL; (d) the surface of the chains was found to be well greased with no noticeable corrosion; and (e) tests included hardness test, optical microscope, scanning electron microscope (SEM), and electron dispersive spectroscopy (EDS) to help determine the type(s) of failure and material composition and to allow us to make recommendations in improving MAAL.

2. Hypothesis

The mode of failure for the chains occurred because of impact fracture. However, it was interesting to note whether the mode of fracture was brittle or ductile in nature. As shown in Figure App-4, a ductile mode of fracture was preferred because it meant that more energy was absorbed by the chains, thereby reducing the impact on the vehicle that the chains were protecting.

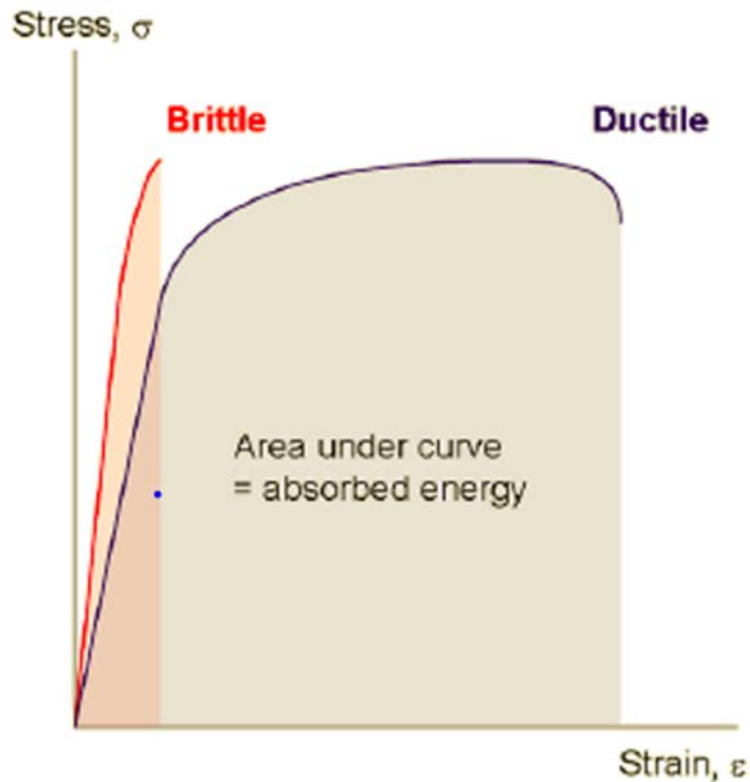


Figure App-4: Stress Strain Curve (Brittle vs Ductile Fracture).

a. *Brittle Fracture*

Brittle fractures occurred without appreciable deformation and propagated through rapid crack movements. The direction of crack propagation was usually perpendicular to the direction of the applied stress and resulted in a relatively flat fracture surface. In addition to the absence of plastic deformation at the macrolevel, brittle fractures usually were characterized by grainy or shiny textures with “chevron” markings pointing to the crack

initiation site. At the microlevel, crack propagation occurred along grain boundaries, depicting intergranular fractures. This phenomena is shown in Figure App-5.

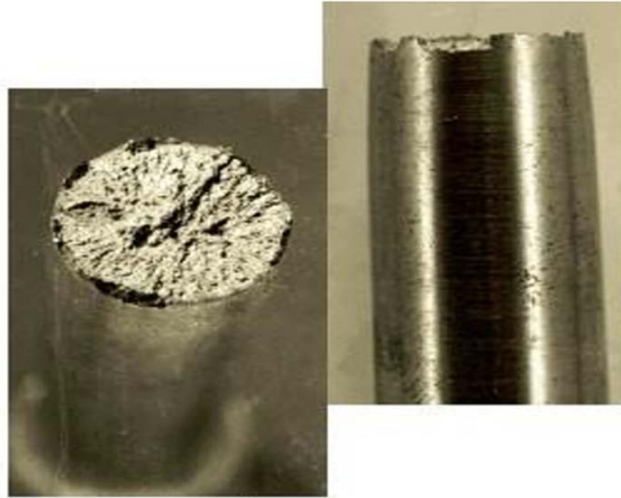


Figure App-5: Brittle Fracture Example (Macro and Micro Appearance).

b. Ductile Fracture

Ductile fractures typically occurred with considerable plastic deformation. Necking usually started with microvoids forming in the interior of the cross-section, which coalesced to form an initial crack that grew in a direction parallel to its major axis. As a result, “cup-and-cone” features were commonly seen at the macrolevel, and they were usually rougher, compared to features seen with brittle fractures. At the microlevel, ductile fractures were usually characterized by “dimple-like” features, as shown in Figure App-6.

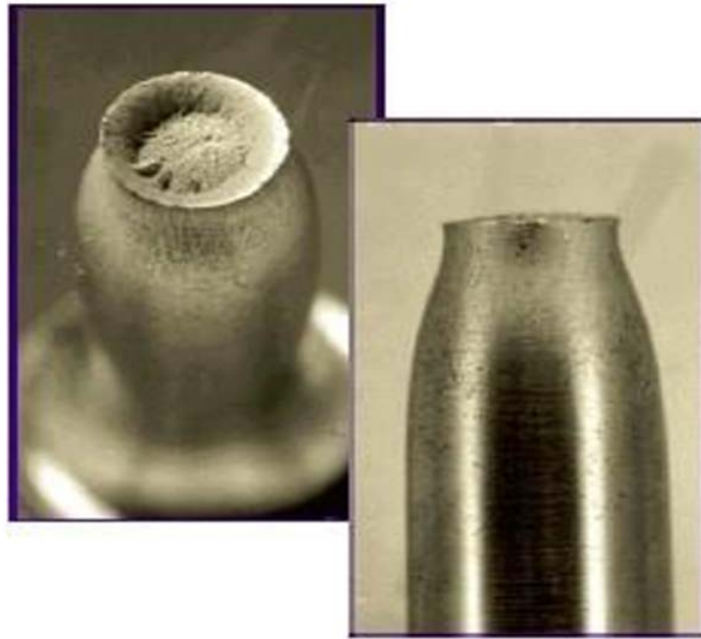


Figure App-6: Ductile Fracture Example (Macro and Micro Appearance).

3. Scanning Electron Microscope and Electron Dispersive Spectroscopy

The SEM produced highly magnified images and greater fields of depth compared to an optical microscope because of the use of electrons and electromagnets instead of light and lenses to create an image. An electron gun at the top of the SEM generated electrons that traveled along a vertical path; an electromagnetic field focused the electron beam onto the sample. The bombardment of electrons onto the sample caused the sample to release electrons that were detected and converted into a signal to produce an image. The images were used to identify ductile and brittle fracture modes visually. Ductile fracture displayed features such as microvoids or dimples that coalesced to create tears or ruptures in the material. Brittle fracture displayed features such as cleavage facets with little to no deformation.

Additionally, accessory equipment on the SEM such as the x-ray spectrometer permitted the detection and analysis of x-rays (accomplished in EDS) to determine the composition of the sample. In EDS, the sample interacts with the electron beam as it does in SEM; however, x-rays instead of electrons are detected and analyzed. As the electron beam strikes the sample, electrons from the beam knock out electrons in shells of atoms within the

sample. In order to fill these holes and minimize potential energy, electrons from higher energy states within the atom drop down to fill the holes, and in doing so, release x-rays that correspond to an energy difference between the two states.

The energies of these x-rays were characterized, providing the identity of the elements within the sample. SEM in conjunction with EDS was used to determine fracture mode and composition of the chain drives. Three samples—40-2, 40-3a, and 40-3b—were placed under the SEM for imaging, and EDS was performed on all samples (40-2, 40-3a, and 40-3b) as well as on a polished sample to determine material composition. Samples analyzed are shown in Figure App-7.



From left to right: 40-2, 40-3a, and 40-3b.

Figure App-7: Samples Analyzed by SEM/EDS.

a. Scanning Electron Microscope (SEM) Results

The SEM images at 3000x and 5000x magnification show dimples or microvoids in the material, indicating the final fracture was ductile in nature. In addition, some of the dimples were “flattened,” suggesting that the material was smashed following plastic deformation and fracture. It is likely that impact from other portions of the chain or flying fragments struck the chain after failure, producing the “flattened” dimples. The dimples had the appearance of being pulled, which was probably a result of being struck by a high velocity object such as a projectile. Figure App-8 shows SEM images of the dimples (left and middle) and flattened dimples (right) of the fractured samples.

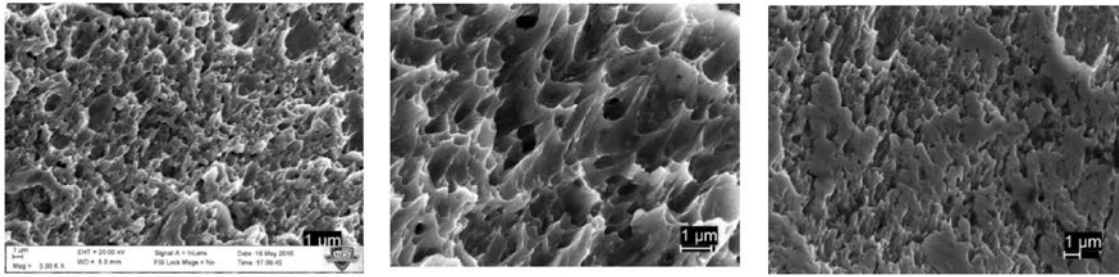


Figure App-8: SEM Images Ductile Fracture (3000x and 5000x).

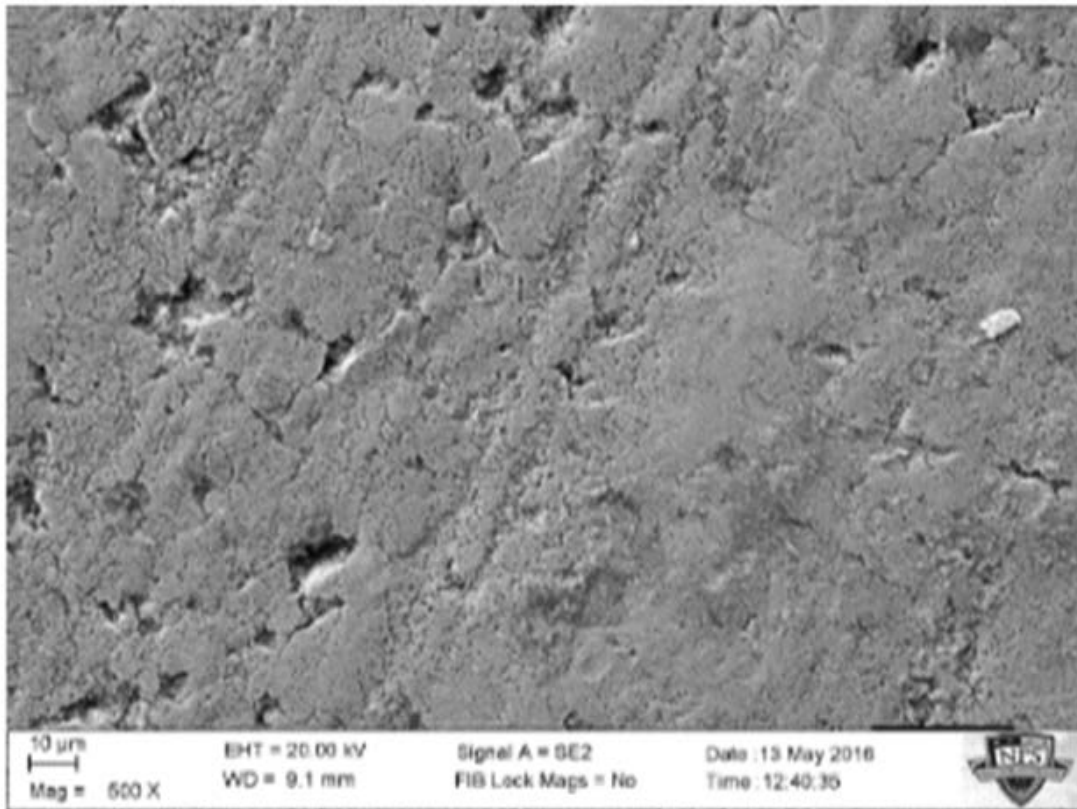


Figure App-9: SEM Image of Surface Outside of Fracture Site.

SEM images captured away from the fracture site show damage on the material's surface, indicating that the chain was exposed to some form of impact energy away from the primary fracture sites.

Images also show that the structure was martensitic in nature because of the needle shaped grains, confirming results obtained by EDS that the material was likely plain carbon steel.

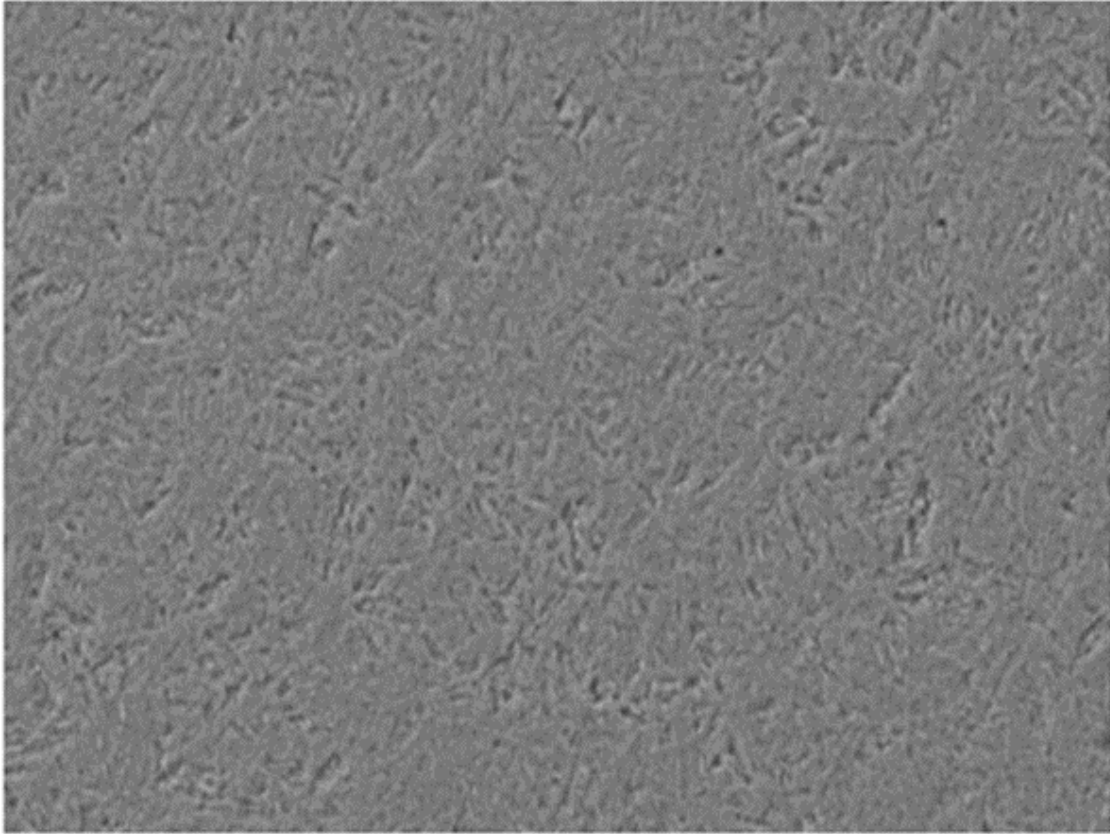


Figure App-10: SEM Image of Martensitic Microstructure.

4. Electron Dispersive Spectroscopy Results

EDS of the original sample shows the drive chains were composed of iron (98 weight% Fe) and trace elements (0.28 weight% Si, 00.14 weight% Cr, and 0.80 weight% Mn), as shown in Figure App-11. The lack of chromium and nickel amounts typical in stainless steel indicate that the material was a plain carbon steel.

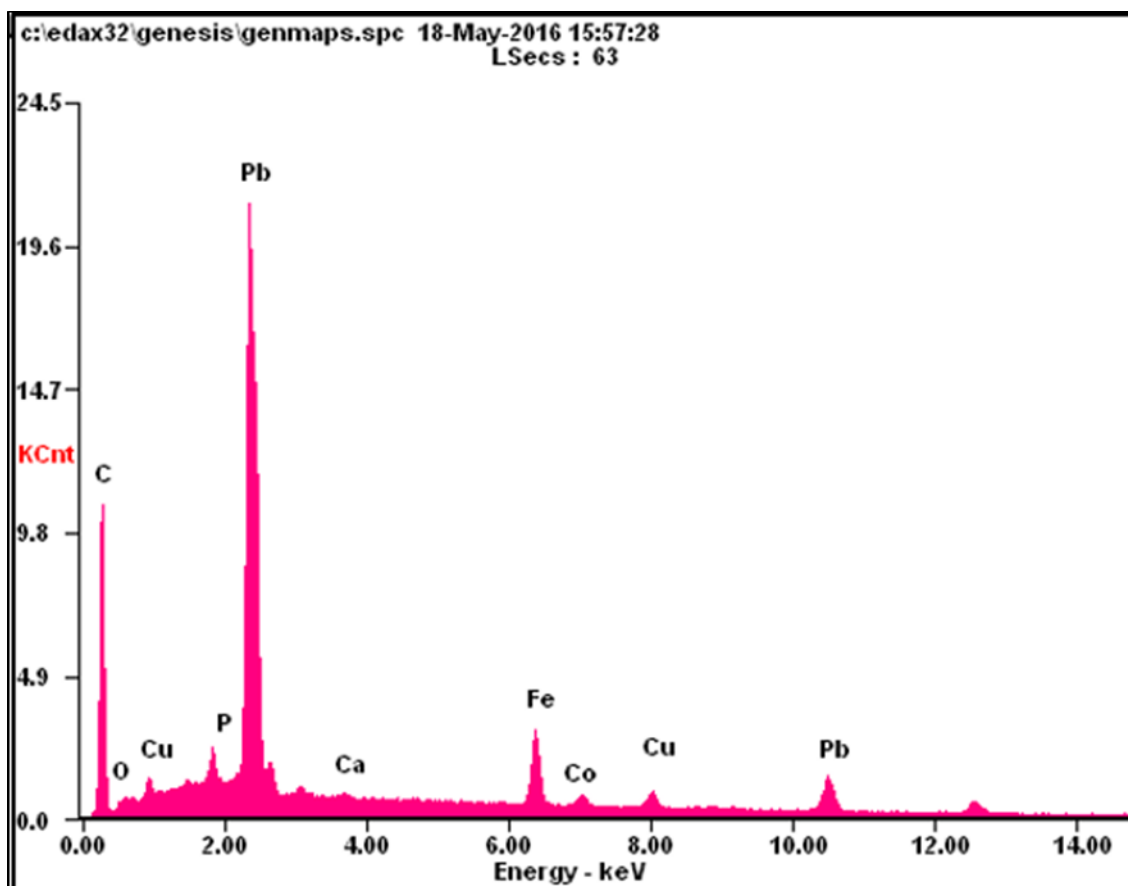


Figure App-11: EDS Results for Original Sample.

EDS was also performed at locations containing a high degree of residue. Figure App-12 shows an SEM image of one such area (boxed in red). The area boxed in red was analyzed using EDS, and the results yielded a high concentration of lead and trace amounts of copper, which was likely a result of the projectile and/or projectile fragments depositing material on the chain drive.

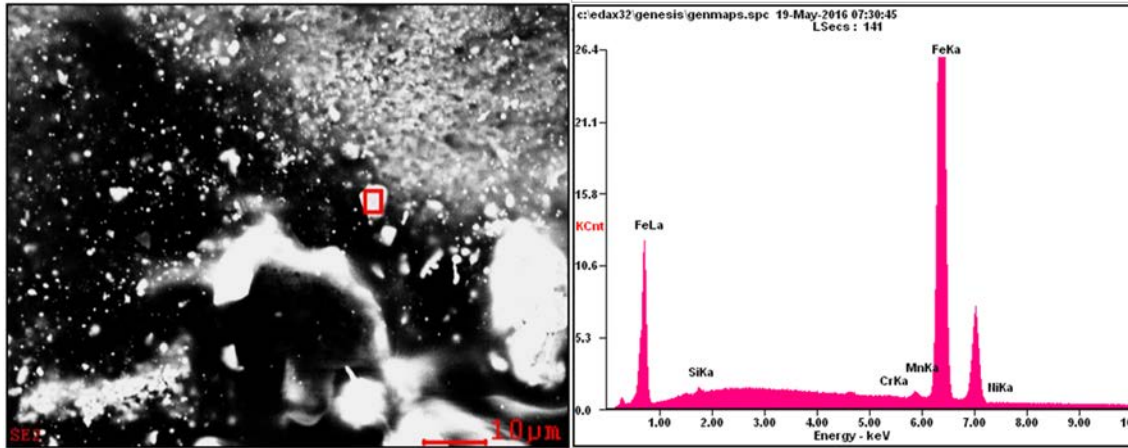
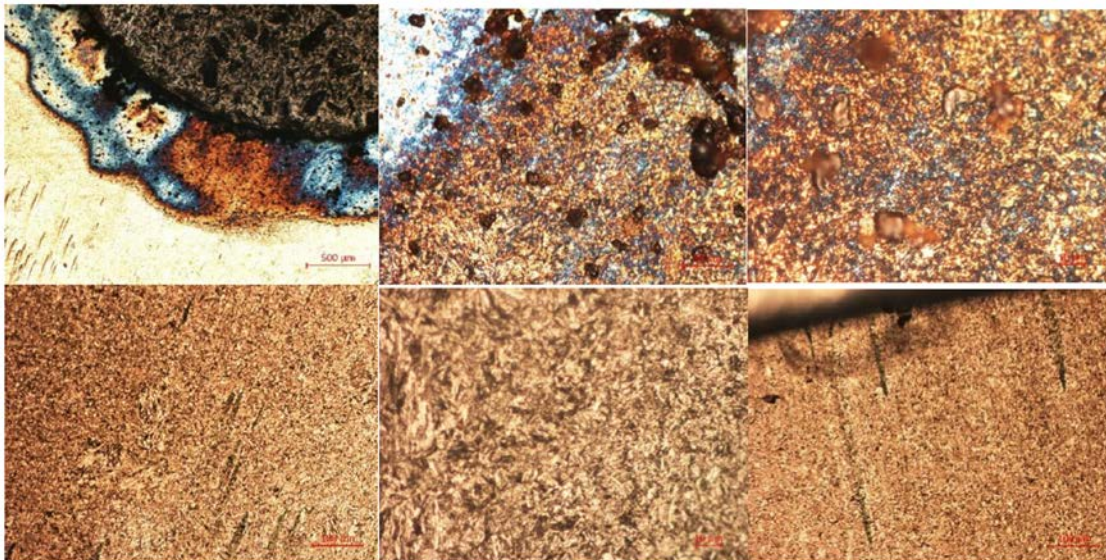


Figure App-12: EDS Results for Fractured Sample.

5. Optical Microscope Results

Two samples of the chains (one each from 40–2 and 40–3) were mounted into pucks and polished. Following acid etching, the samples were examined using optical microscopy at various magnifications. Multiple examples were seen on the surface of what appeared to be impact damage. No telltale signs of brittle fracture were noted (e.g., chevrons). Some general grain elongation was seen, and visual observations supported the conclusion of a ductile failure mode.



Top-left: 25x; Top-middle: 100x; Top-right: 100x; Bottom-left: 500x; Bottom-middle & Bottom Right: 100x magnification.

Figure App-13: Optical Microscope Images of 40–3 MAAL strand.

6. Vickers Hardness Test

The Vickers Hardness Test was used to determine the hardness of the MAAL material. Because the sample from MAAL was relatively small, the Vickers Hardness Test was a better alternative for determining hardness, compared to the Rockwell Hardness Test, which is usually used for larger samples. The Vickers Hardness Test uses a diamond tip in the form of a square-based pyramid. This tip then forms an indentation on the surface of the material. Unlike the Rockwell Hardness Test that measures the depth of indentation, the Vickers Hardness Test observes the surface area of the indentation as compared to the load. Figure App-14 shows the polished samples and the Vickers Hardness Tester evaluating the samples.

Results from the hardness test revealed that the hardness of the fractured sample and that of the unaffected sample were not very much different. In addition, it was found that hardness near the pinhole of the roller links was higher than that at the center of both samples. Finally, the fractured surface revealed a higher hardness, compared to its center, possibly because of strain hardening of the fractured surface. This strain hardening was most likely from manufacturing and not a result of the projectile striking the MAAL.



Figure App-14: Vickers Hardness Tester and Polished Samples.

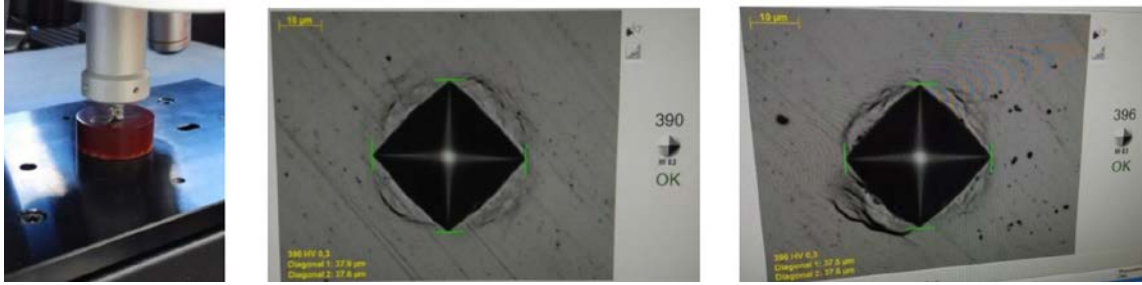


Figure App-15: Center of Original Sample.

7. Final Analysis

From the results described, it was concluded that the chains failed in a ductile manner because of impact from the projectile. At the macrolevel, the chains were observed to have undergone plastic deformation, resulting in rough and elongated surfaces. At the microlevel, the formation of microvoids and dimples seen in the SEM, as well as the trans-granular propagation of the fracture, confirmed that the mode of failure was ductile in nature. In addition, at the fracture sites, copper-toned colors were observed. These were confirmed via EDS to consist of lead and copper, which were constituents of the projectile. This meant that fractures occurred because of the direct impact of the projectile. As seen from the video, fragments from the impact could have also affected other portions of the chains, resulting in secondary or tertiary fracture sites. This was confirmed by the “flattened” dimples in the SEM images. In addition, EDS determined the chains were plain carbon steel, as shown by the low composition of nickel and chromium. SEM also confirmed the martensitic structures of the steel. Hence, we recommend a material of higher ductility be used for the chains.

a. Short-Term Recommendations

Austenitic steels, such as 304 or 316 stainless steel, are recommended as a replacement material for the current chains because of their high ductility. They are usually more than double the ductility of martensitic steels and thus will be better able to absorb and distribute the impact of the projectile. Other options could involve exploring the use of heat treatment and alloying elements to produce a combination of beneficial microstructures and mechanical properties.

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APPENDIX D. GLOSSARY

Adapt: Changing of a process, identity, form, or function to accommodate emerging purposes or situations more effectively.

Adaptive capacity: Adaptive capacity can be defined as a system's ability adapt or absorb a functional disturbance without completely losing operational performance toward a top-level function.

Adaptive performance factors: Adaptive performance factors are the system attributes, factors, or parameters that can be readily changed or adapted to scale a system's functional performance or output.

Adaptive resilience: Is a system attribute which enables a system to adapt its functional traits, structure, process, and/or identity in order to maintain or regain functional effectiveness in satisfying its top-level functional requirements.

Areal density: A measure of mass for complete armor recipe per area, typically pounds per square foot or kilograms per square meter. The measure leaves out the thickness dimension because the complete composition of armor materials is used despite its thickness.

Armor: A shield of a material that serves to prevent, disrupt, or mitigate a penetrating mass/projectile from entering a protected volume.

Attractor: A set of physical properties or states toward which a system tends to converge, regardless of the system's starting conditions.

Attribute: An innate quality, characteristic, or feature of a system.

Complexity: A system trait in which the functional state of the system is not static, cyclic, or random but uncertain.

Degeneracy: A mode of adaption in which an artifact can serve as the means to conduct a prescribed function but is more appropriately qualified to accomplish other functions.

Deterministic: A system trait in which a system always produces the same output from a given starting condition or initial state—in other words, lack of randomness.

Resilience engineering: An engineering field of study whose technical objective is to realize and bring about resistance to functional disruptions or recovery when those disruption produce system failure.

Engineered resilient systems: A DOD acquisition project which applies the tools, processes and other mean to realize resilient system acquisition processes. These processes are aimed at delivering trusted and effective "out of the box" systems which are suitable in a wide range of contexts and easily adapted to many other contexts through reconfiguration or replacement

Robustness: A system state where a broad set of functional states are accommodated at the expense of optimal design and functionality in those functional states. A system which is a jack of many trades, but master of none.

Equifinal, -ility: Like deterministic, a system trait in which the product or result is always the same.

Exaptation: A type of adaptation in which existing means are employed in novel ways when exposed to new environments and challenges.

Extensibility: The ability or capacity of a system to expand its functional capability to achieve new or emerging requirements and functions.

Mass efficiency: An efficiency measure of how an armor design employs its mass defeating a threat projectile. The efficiency is compared to the equivalent required efficiency of rolled homogenous armor. (See Equation 3)

Modularity: A system attribute that describes the degree to which a system's components may be separated and recombined.

Obliquity: The incidence angle in which an armor plate interacts with a threat projectile. (See Figure 39.)

Operational variation: An internal reconfiguration through which the means to accomplish a task are adapted when met with failure.

Top-level function: A top-level function is a system or subsystem's fundamental qualitative function. For example, an armor system's parent function is to prevent penetration. Systems functionally fail when their parent function cannot be achieved.

Parasitic Capacity: Underutilized functional capability that detracts from adjacent functional capability within a system.

Perturbation: A disruption of a system or process from its regular or normal state of function, caused by an outside influence.

Progressive scaling: An external reconfiguration in which the magnitude of the contributing means is adaptively scaled to accomplish the task.

Reallocation: An internal reconfiguration in which similar unemployed means are pulled from another area of a system to contribute to the accomplishment of a task.

Recovery: A systems ability to adapt functional traits and attributes along adaptive performance factors in order to top-level functionality in the face of severe perturbation. For example, an armor system with inherent recovery abilities could reconfigure its adaptive performance factors in a fashion that enabled it to regain and maintain its parent functionality to protect against a threat after it has been penetrated by that threat

Redundant scaling: An external reconfiguration in which the means contributing to the accomplishment of a task is adaptively duplicated and thus scaled to accomplish the task.

Resilience: A system attribute that describes the system's ability to withstand, resist, or recover from functional perturbations and disruptions.

Resistance: A system's innate ability to withstand or overcome a diverse set or magnitude functional challenges and/or perturbations and maintain top-level functionality. For example, a highly resistant armor has the ability to withstand penetration from a broad range of penetrating threats, or several impacts from the same threat.

Trait: A distinguishing quality or characteristic of a system.

Trajectorial mass: The mass of the volume of material on the same trajectory and width/diameter of the threat projectile.

V₅₀ ballistic limit: The ballistic limit or limit velocity is the velocity required for a particular projectile to have a 50% probability to penetrate a target or armor.

Validation: A set of tests, experiments, and actions used to check the compliance of a system element, process, or task requirements with its purpose and functions.

Verification: A set of tests, experiments, and actions used to check the correctness of a system element, process, or task requirements with its purpose and functions.

Volumetric efficiency: An efficiency measure of how an armor design employs its volume defeating a threat projectile. The efficiency is compared to the equivalent required efficiency of rolled homogenous armor. (See Equation 4.)

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